EVAPOTRANSPIRATION FROM CYPRESS (*Taxodium ascendens*) WETLANDS AND SLASH PINE (*Pinus elliottii*) UPLANDS IN NORTH-CENTRAL FLORIDA

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1996

ACKNOWLEDGEMENTS

I am especially grateful to my major advisor, Dr. Hans Riekerk, for his encouragement, guidance and patience. It is his vision, help and confidence in me that makes my study and dissertation in the United States possible.

I am also very grateful to my supervisory committee, Dr. Henry Gholz, Dr. Loukas Arvanitis, Dr. Ken Campbell, and Dr. Allen Smajstrla, for their many suggestions. Dr. Henry Gholz advised on the initial taking off of the campaign on stomatal conductance measurements, and allowed me to use the independently measured eddy covariance data to verify my models.

I would like to thank Dr. Wendell Cropper, Jr., for his tremendous help when he was working at the University of Florida and served on my committee. Now, he is working at the University of Miami, Florida.

I am indebted to my friends and colleagues, especially Larry Korhnak, who collected all the long term field data including water table fluctuations and weather information during these years. Willie Wood helped with data collection on litterfall and throughfall. Ken Clark ran the Eddysol System for eddy correlation data. Robert Hamlin climbed the towers with me to measure transpiration and stomatal conductance. Ge Sun helped in setting up the access towers and getting the truck out of swamps when stuck.

Finally, I want to thank my wife, Hongmei Luo, for her full support and patience.

This research was supported by USDA Forest Service Grant Contract No. A8FS-91961: Evapotranspiration Processes in Pine-cypress Flatwoods Wetlands, Hans Riekerk, principal investigator, and conducted on the lands made available by the Georgia-Pacific Corporation.

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Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy

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May 1996

Chairperson: Hans Riekerk
Major Department: Forest Resources and Conservation

In order to investigate the difference, if any, of evapotranspiration between cypress wetlands and slash pine uplands, the rainfall interception, evaporation from water surface, transpiration and stomatal conductance at the leaf/needle level, leaf area index, soil moisture and water table fluctuations were measured in three cypress (*Taxodium ascendens*) wetlands and their surrounding slash pine (*Pinus elliottii*) plantations from April 1993 to March 1994 near Gainesville, Florida. The feasibility and potential methods of estimating evapotranspiration from water table fluctuations were appraised and developed. A multi-species and multi-layer evapotranspiration model at ecosystem level, ETM, was developed in order to simulate the change of evapotranspiration and its components (i.e., transpiration, rainfall interception, and evaporation from water or soil surface) under various environmental and biological conditions. The transpiration submodel, which scales transpiration up from the leaf/needle level using the acquired stomatal conductance data and information about stand structure and micrometeorology, was verified with field scale measurements obtained in a slash pine plantation by an eddy-correlation method. There were no empirical parameters in the newly-derived interception submodel, which was tested by field measurements and compared with Gash and Mulder models using data from the literature. A submodel of evaporation from open water surfaces was also developed, based on field measurements.

There was no significant difference ($\alpha=0.05$) between cypress and slash pine with respect to transpiration and stomatal conductance at the leaf level during the growing season. No significant difference ($\alpha=0.05$) has been detected in terms of annual transpiration, rainfall interception and total evapotranspiration between cypress wetlands and slash pine uplands. However, evapotranspiration from wetlands during the wet year of 1992 was significantly higher than that during the drier years (e.g., 1991 and 1993) or that from pine uplands. Therefore, the difference in evapotranspiration between cypress wetlands and slash pine uplands was primarily determined by the magnitude of water surface evaporation in wetlands, which could be as high as 500 mm per year or about 1/3 of the potential evaporation.

CHAPTER 1
INTRODUCTION

Evapotranspiration (ET) is one of the major processes within the hydrologic cycle, second only to precipitation in the water cycles of most subtropical ecosystems. The soil water, runoff and groundwater recharge regime of an area is largely affected by ET. This is an important consideration in the planning and management of water resources. Consequently, the need to predict ET for management options in different environments is increasing (Hatfield, 1988; Saxton and Cordery, 1988).

As the human population increases, fresh water resources are being tapped to their limit, at least nearby large cities. Although transferring fresh water from one region to another is technically possible, other factors such as political and water rights issues, make it very difficult. One way to alleviate water shortage is to reduce the consumptive use of water by vegetation. Although ET in natural ecosystems is inevitable, the magnitude of the water loss can be regulated to some degree by manipulation. For example, reduction of ET from agricultural lands by using a mulch ground cover has been practiced for thousands of years. At the local/regional scale, changing plant species or vegetation types can also regulate the consumptive use to a certain degree (e.g., Newson and Calder, 1989). However, detailed information about the variation of ET under various environmental conditions is needed for this purpose, but is generally not available.

Slash pine (*Pinus elliottii*) uplands and cypress (*Taxodium ascendens*) wetlands are two important forest ecosystems in the flatwoods landscape of the southeastern U.S. coastal plain (Ewel and Odum, 1984). Although both ecosystems play an important role in environmental protection, slash pine uplands are mostly cultivated because of their capability to produce timber, while the cypress wetlands are mostly recognized for their value for wildlife, flood control, groundwater recharge and waste water purification at local and regional scales (Ewel and Odum, 1984; Ewel, 1990). The function of wetlands is directly related to their hydrology, which has a prolonged hydroperiod. Wetlands are nature's water regulation system, storing water in periods of excess and releasing it in periods of water shortage (Odum and Ewel, 1984; Riekerk, 1989).

At the beginning of this study, it was unknown as to which species (cypress vs. slash pine) or ecosystem (cypress wetlands vs. pine uplands) uses more water in Florida flatwoods (Riekerk, 1989; Ewel and Smith, 1992). The answer to this question has significant implications for the comprehensive management and planning of the flatwoods landscapes in Florida (Odum, 1984; Ewel, 1990). To adequately answer this question or to predict ET for various management scenarios, it is necessary to understand the changing patterns of the different components of ET, including rainfall interception, transpiration, and evaporation from the substrate (soil or water). In terms of transpiration, it is necessary to understand the processes occurring at the leaf/needle and canopy levels. In other words, transpiration, therefore ET, should be understood at various temporal (e.g., instantaneously, hourly, daily and annual) and spatial (e.g., leaf/needle, stand and regional) scales.

Besides its significance in terms of affecting local/regional water resources, the possible difference of ET between cypress wetlands and their surrounding slash pine uplands, along with the heterogeneous spatial distribution of specific yield (water produced per unit water table drop, both in depth), is probably an important factor affecting the direction and velocity of subsurface flow in Florida flatwoods. Pine flatwoods are characterized by fairly flat topography, high water tables, low nutrient availability, and sandy soils with deep percolation limited by underlying clay formations in most areas.

A well-verified model based on readily available information is required in order to predict ET of cypress wetlands and slash pine uplands under various conditions, and to better understand the hydrological, chemical and biological interactions between wetlands and uplands, and therefore to facilitate forest water management. This model should have the capability to predict the total flux of water vapor leaving these ecosystems under all conditions, including various weather conditions, differences in species composition and stand structure (e.g., leaf area distribution in space and time), and substrates (soil or water).

The major objective of this dissertation was to test for significant ET differences between the cypress wetlands and slash pine uplands. The null hypothesis to be tested was that there is no difference in ET between cypress wetlands and slash pine uplands in the pine flatwoods. To accomplish the above objective, the following tasks have been identified:

1) Measure transpiration and stomatal conductance (g_s) to water vapor of slash pine and cypress at the leaf/needle level;

2) Analyze the relationship between stomatal conductance and environmental variables;
3) Develop stomatal conductance models for both species using readily available meteorologic information;
4) Compare the transpiration and stomatal conductance of cypress and slash pine at the leaf/needle level;
5) Scale up stomatal conductance from leaf to forest stand level;
6) Develop a general rainfall interception submodel and apply it to wetlands and uplands;
7) Measure and predict evaporation from the water surface of wetlands and that from the forest floor;
8) Develop a multi-layer multi-species ET model at the ecosystem level;
9) Investigate the degree of coupling between a forest canopy and the atmosphere and its change with biological and environmental variables;
10) Compare to evaluate if there is any ET difference between cypress wetlands and slash pine uplands.

CHAPTER 2
LITERATURE REVIEW

Evapotranspiration from Florida Flatwoods

Brown (1978) measured transpiration rates of cypress leaves with an infrared CO_2 analyzer in six cypress domes in Florida. Using a very simple scaling-up method, Brown (1978) found that 70-93% of the total water loss in these forests occurred via transpiration. The differences in transpiration rates among different types of domes and among canopy levels were found to be significant, and were partially attributed to differences in saturation deficit of the air. However, no detailed analysis was made of the relationship between transpiration and radiation and air temperature. These data were collected from different cypress domes, under different atmospheric conditions of humidity, wind and sunlight, within about one or two months for each dome, and without parallel measurements between any two cypress domes. So it is quite difficult to estimate the annual ET and therefore to compare the transpiration between these domes. In addition, the method used to scale transpiration rate from leaf up to canopy level appears to be too crude because transpiration varies with many environmental as well as biological variables.

The lysimetric (mass balance) method has been applied to measure the ET of a single young slash pine tree growing in a poorly drained flatwoods soil (Riekerk, 1985a, 1985b). ET measured using this method reflects the integrated impact of the soil water regime, solar radiation, air temperature, vapor pressure deficit (VPD) and probably root aeration on ET. The derived monthly crop factors (the ratio of ET to potential ET) were applied to a number of slash pine ecosystems without considering the differences in ecosystem structure and environmental conditions (Riekerk, 1985a; 1985b; 1989; Phillips, et al., 1989). This might introduce considerable uncertainty in the results.

Because of the existence of standing water in wetlands and high water table in pine flatwoods uplands, it is possible to estimate ET from water level fluctuations. The method is well-established theoretically (White, 1932). When there is no rainfall:

$$ET = s\ (wt_{24} - 6\ wt_{04}) \tag{2-1}$$

where s is specific yield (water released corresponding to a unit decrease in water level), wt_{24} and wt_{04} are water level changes after 24 hours and 4 hours from midnight, respectively. Water level change from midnight to 4 am is assumed to be caused solely by lateral flow and deep percolation, to be the average for that day, and used to estimate the daily net loss of lateral and deep percolation.

If only the standing water and not the soil part is being considered, the specific yield of wetlands is one. Based on the above-mentioned method, a wide range of ET has been reported for isolated Florida cypress wetlands (Heimburg, 1984; Ewel and Smith, 1992). Excluding interception, annual ET varied from 860 to 870 mm in two wetlands

(Heimburg, 1984) and from 380 to 860 mm in another three wetlands (Ewel and Smith, 1992). Because water is seldom a limiting factor in wetlands and the transpiration rate of cypress is not so different from slash pine (see Brown, 1981; Riekerk et al., 1993), the low values reported are not likely to be valid for this region, which has a pan evaporation of about 1670 mm per year (Dohrenwend, 1978). The low values probably resulted from the weakness of the method as applied, which divided the evaporated water volume by the maximum wetland area. The reduction of water storage in the peat or the soil which is not covered by standing water was not considered. This method will also definitely underestimate ET from wetlands when the water level is below its maximum. The lower the pond water level, the smaller the wetland area covered by standing water, the less reliable the results.

Except for the abnormal low value reported, ET (including 260 mm interception, Heimburg, 1984) from wetlands seems comparable to that from pine flatwoods (Golkin, 1981; Riekerk, 1985a; 1985b; 1989). However, at present we can not tell if there is any difference in ET between wetlands and surrounding uplands for a given condition because the limited data is based on different methods and from different stands. The ET difference of slash pine uplands and cypress wetlands may vary with the characteristics of these ecosystems, such as age, stem density, species composition and cypress wetland size, as well as with environmental conditions. Therefore, it is necessary to establish a predictive model, being driven by ecosystem parameters and environmental variables, to estimate the ET of these different ecosystems.

Single Layer Models

Evaporation from natural surfaces is commonly estimated with the classical Penman equation (Penman, 1948) . The original Penman formula was derived for lake evaporation and applied to a well-watered grass surface. The Penman formula can readily be modified to describe the evaporation rate from a dry surface when the surface conductance to vapor transfer between the level where evaporation takes place and the interface with the atmosphere is specified (Penman, 1953; Monteith, 1973). The Penman formula has been extended by Monteith (1965) to estimate the ET of a stand of vegetation when considered as one "big leaf". It takes the form of:

$$\lambda E = \frac{\varepsilon\,(R_n - G) + \rho c_p D_a g_a/\gamma}{\varepsilon + (1 + g_a/g_c)} \qquad (2\text{-}2)$$

where λ is the molar latent heat of vaporization, in J mol^{-1};

E is the flux of evaporated water, in mol m^{-2} s^{-1};

R_n and G are net radiation and ground heat flux respectively, in W m^{-2};

D_a is the saturation vapor pressure deficit of the ambient air, in Pa;

ρ is air density, in kg m^{-3};

c_p is the molar specific heat of dry air at constant pressure, in J mol^{-1} K^{-1};

γ is the psychrometric constant, evaluated at surface temperature, in Pa K^{-1};

g_c and g_a are canopy conductance and aerodynamic conductance, respectively, in mol m^{-2} s^{-1};

ϵ, or Δ/γ, is the dimensionless ratio of the increase of latent heat content to the increase of sensible heat content of saturated air, where Δ is the derivative of the saturation vapor pressure with respect to temperature evaluated at air temperature, in Pa K^{-1}.

Although the Penman-Monteith equation has been applied successfully in many situations, it has been challenged conceptually (see Lhomme, 1991). It is assumed in the Penman-Monteith equation that the canopy exchanges sensible and latent heat with the atmosphere from a theoretical surface located at the same level as the effective sink of momentum, i.e. level $d+z_0$ above the ground (Figure 2-1). The roughness length d specifies the mean height at which momentum is absorbed by the individual elements of the forest, while the zero displacement height z_0 specifies the bulk effectiveness in absorbing the momentum. Aerodynamic conductance is calculated between this level $d+z_0$, where fluxes are supposed to originate, and the reference height above the canopy. However, the canopy can not be considered theoretically as a system exchanging sensible and latent heat from the same level as is assumed in the single-layer approach (Lhomme, 1991; Paw U and Meyers, 1989). It has been demonstrated based on higher-order closure principles, that the concept of a single effective source-sink height is not easily applicable to plant canopies because of the erratic behavior of the zero displacement plane for water vapor and heat (Paw U and Meyers, 1989).

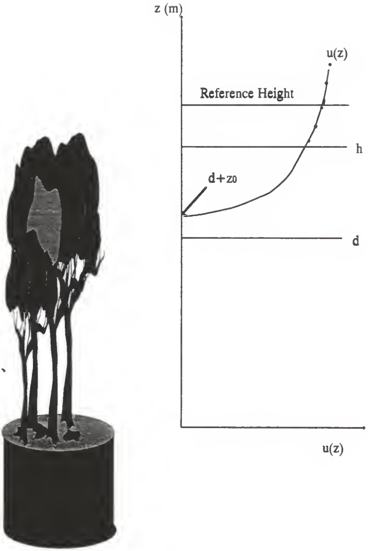


Figure 2-1. The relationship between canopy height (h), roughness length (z_0), zero displacement height (d), and wind speed (u(z)) in a forest.

The canopy surface conductance computed from the Penman-Monteith equation based on ET at the canopy level ("top-down" method), and the canopy stomatal conductance that is derived as the product of leaf porometry and LAI measurements ("bottom-up" method), are often used interchangeably (e.g., Jarvis and Morison, 1981; Roberts et al., 1993; Lindroth et al., 1994). However, it has been shown theoretically (Stewart and Thom, 1973; Shuttleworth, 1976; Finnigan and Raupach, 1987; Lhomme, 1988a, 1988b; Paw U and Meyers, 1989) and experimentally (Baldocchi et al., 1987) that these two measures of canopy conductance may not be the same. It is now clear that the canopy conductance of the Penman-Monteith combination equation includes stomatal, air and surface conductances (Finnigan and Raupach, 1987; Lhomme, 1988a; 1988b).

It was also demonstrated that the Penman-Monteith equation only holds true when the soil surface conductance of vapor is of the same order of magnitude or smaller than the stomatal conductance of the lowest layer of vegetation (Lhomme, 1988b). In other words, ET with significant below-canopy evaporation can not be adequately described by a single-layer combination equation.

Multi-Layer Models

The multi-layer approach has been developed to estimate sensible and latent heat fluxes because of the complexity of energy transfer and gas exchange in the canopy, and the inapplicability of the single-layer combination equation for many situations (Waggoner and Reifsnyder, 1968; Shuttleworth, 1976; Shuttleworth and Wallace, 1985; Lhomme, 1988a; 1988b). Multi-layer models are based on theories of energy transfer in a canopy with structural information. Most of these models are able to incorporate the substrate (soil or water) contribution to the total latent heat flux. Therefore, models based on the multi-layer concept can be applied to more diverse situations.

Shuttleworth (1976) derived a general combination equation based on the continuous multi-layer method. Because of its tremendous data requirements, this equation cannot be used as a practical tool for prediction. Subsequently, Shuttleworth and Wallace (1985) derived a two-layer Penman-Monteith type equation, assuming that latent heat flux originates from two conceptual layers, the plant canopy (subscript c) and the substrate (subscript s), to describe the contribution of evaporation from plants and from the substrate:

$$\lambda E = C_c PM_c + C_s PM_s \tag{2-3}$$

where PM_c and PM_s are terms similar to the Penman-Monteith combination equation which would apply to evaporation from a closed canopy and from bare substrate, respectively. They have the form:

$$PM_c = \frac{\Delta(Rn-G) + [\rho c_p D - \Delta r_a^c (Rn_s - G)]/(r_a^a + r_a^c)}{\Delta + \gamma[1 + r_s^c/(r_a^a + r_a^c)]} \tag{2-4}$$

$$PM_s = \frac{\Delta(Rn-G) + [\rho c_p D - \Delta r_a^s (Rn - Rn_s)]/(r_a^a + r_a^s)}{\Delta + \gamma[1 + r_s^s/(r_a^a + r_a^s)]} \tag{2-5}$$

where D is vapor pressure at reference height, Rn_s is net radiation flux into the substrate, G is soil heat flux, r_a^a is aerodynamic resistance between canopy source height and reference level, r_a^c is bulk boundary layer resistance of the vegetative elements in the canopy, r_a^s is aerodynamic resistance between the substrate and canopy source height, r_s^c is bulk stomatal resistance of the canopy, and r_s^s is surface resistance of the substrate.

The coefficients C_c and C_s are given by the expressions:

$$C_c = \frac{1}{1+R_c R_a / R_s (R_c + R_a)}$$
$$C_s = \frac{1}{1+R_s R_a / R_c (R_s + R_a)}$$

with

$$R_a = (\Delta+\gamma)\, r_a^a$$
$$R_s = (\Delta+\gamma)\, r_a^s + \gamma r_s^s$$
$$R_c = (\Delta+\gamma)\, r_a^c + \gamma r_s^c$$

It has been shown that this approach was better suited to partial canopies than the Penman-Monteith method (e.g., Saugier and Katerji, 1991).

Lhomme (1988a, 1988b) derived general expressions for sensible and latent heat fluxes starting from a discrete approach using an electrical analog method. This method was first used by Waggoner and Reifsnyder (1968) to describe the latent and sensible heat transfer in vegetation. These expressions are valid for both single- and multi-layer models. The formula for latent heat flux (Lhomme, 1988a) will be presented later.

Coupling Between Vegetation and the Atmosphere

It is widely understood by plant physiologists and ecologists that stomata play a dominant role in regulating transpiration from vegetation (Idso, 1983; Jarvis and McNaughton, 1986; Meinzer, 1993). On the other hand, micrometeorological models often predict canopy transpiration adequately without explicit consideration of stomatal responses (Jarvis and McNaughton, 1986). In order to demonstrate and quantify the importance of stomatal control of transpiration at various spatial scales, the Ω coefficient has been used to define the degree of decoupling between vegetation and the atmosphere (McNaughton and Jarvis, 1983; Jarvis and McNaughton, 1986; Martin, 1989; McNaughton and Jarvis, 1991; Pinty et al., 1992). The value of the decoupling factor Ω varies between zero and 1. A low value of Ω indicates a well-coupled system controlled mainly by stomatal or canopy conductance, while a high value indicates a decoupled system controlled mainly by available energy. Forest ecosystems are generally well-coupled with the atmosphere overhead, therefore the Ω values are low. The representative value for forests is about 0.1 or 0.2, while for agricultural crops Ω can be as high as 0.9 (Jarvis and McNaughton, 1986).

The sensitivity of transpiration to a change in stomatal conductance can be expressed as (McNaughton and Jarvis, 1983; Jarvis and McNaughton, 1986):

$$\frac{dT_r}{T_r}=(1-\Omega_s)\frac{dg_s}{g_s} \quad \text{.............. for a single leaf}$$
$$\frac{dT_r}{T_r}=(1-\Omega_c)\frac{dg_c}{g_c} \quad \text{.............. for a whole canopy} \qquad (2\text{-}6)$$

where T_r is transpiration rate, Ω_s and Ω_c are the decoupling factors at leaf and canopy levels, respectively, and g_s and g_c are leaf stomatal conductance and canopy (stomatal) conductance, respectively.

From the Penman-Monteith combination equation:

$$\lambda E=\frac{\varepsilon(R_n-S)+c_p\rho D_a g_a/\gamma}{\varepsilon+1+g_a/g_c} \qquad (2\text{-}7)$$

we can see that when the surface-layer aerodynamic conductance g_a becomes very small, the equation approaches the limit:

$$\lambda E_{eq}=\frac{\varepsilon}{\varepsilon+1}(R_n-S) \qquad (2\text{-}8)$$

This is the evapotranspiration rate that would occur from vegetation that was decoupled from the atmosphere above the canopy by very thick boundary layers. It is often known as the "equilibrium evaporation rate" with high Ω values (e.g., Slatyer and McIlroy, 1961; Jarvis and McNaughton, 1986). If the vegetation is largely decoupled from the atmosphere above the canopy, or leaves from the ambient air, VPD in the canopy or around the leaves will become dependent on the transpiration rate, and vice versa, so that the transpiration rate will become close to the equilibrium rate. In contrast, if the boundary-layer conductance is very high, and the vegetation is well-coupled to the atmosphere, the Penman-Monteith equation approaches the limit:

$$\lambda E_{imp}=\frac{c_p\rho}{\gamma}VPD\,g_c \qquad (2\text{-}9)$$

This is often known as the "imposed evaporation rate" with low Ω values, because the VPD in the ambient air is directly imposed on leaves and largely independent of the evaporation rate.

At the ecosystem level the ET rate is always between these two extremes and can be described by:

$$E=\Omega E_{eq}+(1-\Omega)\,E_{imp} \qquad (2\text{-}10)$$

If the ratios of leaf stomatal to boundary-layer conductance and of the canopy to surface-layer conductance are high, we need only crude models of stomatal responses, but when they are low, we need much better models (McNaughton and Jarvis, 1991). In aerodynamically rough coniferous forests with low ratios of stomatal to boundary-layer conductance and of canopy to surface-layer conductance, the vapor pressure of the bulk air is mostly imposed at the leaf or canopy surface resulting in strong stomatal control of transpiration (low Ω value). As a result, more accurate g_s models are required for coniferous forests, especially those with large gaps or discontinuous canopies.

Modeling Stomatal Conductance at the Leaf Level

Transpiration, a process characterized by water vaporization in substomata and diffusion through stomata into the ambient atmosphere, is directly controlled by the transmissivity of stomata in plant leaves. Characteristics of gas exchange between a plant and the ambient atmosphere through the stomata of individual leaves can be described by Fick's law using stomatal conductance (g_s) (Nobel, 1971; McDermitt, 1990):

$$g_l = \frac{P}{VPD} * Tr = \frac{g_s g_b}{g_s + g_b} \qquad (2\text{-}11)$$

where g_l and g_b are leaf conductance and leaf boundary-layer conductance, respectively, VPD is the vapor pressure gradient from the leaf surface to the ambient air, P is the atmospheric pressure, and Tr is the transpiration rate. The number of stomata per unit leaf area and the characteristics (e.g., shape, area, perimeter, depth, hairiness) of stomata vary greatly between species, and so is stomatal conductance (Jarvis and Mansfield, 1981; Turner, 1991).

Stomatal conductance is controlled by many biological and environmental factors. The major controlling factors include: photosynthetically active radiation (PAR), leaf temperature (which determines the saturated vapor pressure in substomata), VPD from leaf to the ambient atmosphere, leaf water potential, and soil moisture status (Jarvis, 1976; Jarvis and Morison, 1981; Turner, 1991; Ball, 1988). The general relationship between stomatal conductance and the controlling variables has been studied extensively both in the laboratory and in the field (Jarvis and Mansfield, 1981; Turner, 1991). Because g_s is controlled by so many factors, it is often difficult to get a close relationship between stomatal conductance and any individual biological or environmental variable. The value of stomatal conductance expected for a particular controlling variable is often reduced due to the influence of other variables. Therefore, when stomatal conductance is plotted against any individual controlling variable a highly scattered diagram results.

Jarvis (1976) suggested using a boundary-line or "envelope" analysis method to interpret the large variation of stomatal conductances observed in the field. In this method, it is assumed that stomatal conductance is affected by non-synergistic interactions between or among plant and environmental variables:

$$g_s = g_m f_1(PAR)\, f_2(\Delta e)\, f_3(T_l)\, f_4(\psi_s) \ldots \qquad (2\text{-}12)$$

where g_m is the maximum stomatal conductance when there is no environmental restriction and the functions f_1, f_2, f_3 and f_4 represent the limiting influences from PAR, vapor pressure difference from stomatal cavity to leaf surface (Δe), leaf temperature (T_l), and soil water potential (ψ_s). These functions range in value between zero and one.

Although Jarvis' empirical multiplicative model has been widely used (e.g., Avissar et al., 1985; Dolman et al., 1988; Baldocchi et al., 1991; Dickinson et al., 1991), a few comparisons of simulation models showed that empirical models based on other concepts were as effective as the Jarvis model (Chambers et al., 1985; Kaufmann, 1984; Ball, 1988; Collatz et al., 1991; Massman and Kaufmann, 1991; Liu et al., 1995). Another empirical model (Ball, 1988), which uses relative humidity and intercellular CO_2 concentration, has been tested recently and showed better accuracy (Ball, 1988).

Canopy Stomatal Conductance

Porometric measurements are usually taken at the leaf or branch level. One major problem with these measurements is how to scale them up from leaf to canopy level (Jarvis and McNaughton, 1986). Because environmental and biological conditions change from leaf to leaf, branch to branch, tree to tree, and site to site, it is only possibly to scale these data up statistically. The first step in scaling is often to try to establish a model of leaf stomatal conductance g_s. The behavior at canopy level can then be obtained by using a g_s model conbined with the spatial distribution of independent variables (i.e., PAR, Δe, T_l) in the canopy. MAESTRO (Wang and Jarvis, 1990) is one such model of high complexity. In most cases, simpler methods are used (e.g. Roberts et al., 1993) where the canopy is often divided into several layers. The light attenuation through these layers is predicted by the Beer-Lambert law (Roberts et al., 1993). In most cases, only the vertical distribution of radiation and LAI have been considered (e.g., Roberts et al., 1993). However, stomatal conductance is controlled by other factors if PAR exceeds a critical value (Jarvis and Mansfield, 1981; Liu et al., 1995). The g_s is usually not controlled by PAR except at low solar elevation angles or at the bottom of the canopy where PAR is smaller than the critical PAR value. As a consequence, it is often mpre desirable to scale g_s up using multiple variables.

Leaf Area Index and Radiation Transfer in Forest Canopy

Leaf area index (LAI) is a very important factor for energy transfer, and CO_2, vapor and other trace gas exchanges between a forest ecosystem and the atmosphere. It is necessary to know LAI and its changes in time and space in order to extrapolate leaf-level measurements to ecosystem or even landscape levels.

The seasonal variation of LAI, litterfall and light penetration have been studied in slash pine forests (Hendry and Gholz, 1986; Dalla-Tea and Jokela, 1991; Gholz et al., 1991). Annual destructive sampling and monthly measurements of needle elongation and needle fall were used to establish monthly LAI values. It was found that the pattern of cumulative litterfall could be fitted by the logistic curve (Gholz et al., 1991; Dalla-Tea and Jokela, 1991), and temporal variation of needle fall could be modeled using stand basal area and the climatic conditions of the spring of the previous year (Gholz et al., 1991).

Allometric growth relationships of cypress have been used to calculate the LAI from total leaf biomass and ratios of leaf area to biomass (Mitsch and Ewel, 1979; Brown, 1978). The LAI of broadleaved trees in cypress wetlands was also determined by this method (Brown, 1978). Although annual leaf litter was collected at some cypress wetlands, litterfall information has not been used to re-establish the dynamics of LAI (Brown, 1978). Cypress leaves of immature trees appear to be compound, whereas in fact each 'leaflet' is a needle growing from the current year's twig. Most of the cypress leaflets of mature trees do not spread out from the current twigs so that one twig plus all adhering leaflets looks like a knobby "needle" that drops off during the fall season. For measurement purposes, Brown (1981) considered a current twig plus its leaflets a whole leaf or "needle".

A number of indirect LAI methods based on radiation transfer in the forest canopy have been developed over the last two decades (Welles, 1990 ; Norman and Campbell, 1991). It was not clear until recently that the value obtained based on radiation transfer theories is always half the total surface area index (SAI) (Lang, 1991; Chen and Black, 1992b). The SAI is the sum of LAI, branch area index and stem area index. As a result, an adjustment is needed to interpret the published results using projected or all-sided LAI rather than half of the total SAI. Gholz et al (1991) applied DEMON, which is based on gap fraction or direct beam theory (Nilson, 1971; Lang and Xiang, 1986; Lang, 1987), to estimate LAI in slash pine forests, and found that it could be used to estimate the long-term average LAI, but not the seasonal changes.

Photosynthetically-active radiation above and below the canopy was monitored in slash pine forests using photodiodes (Gholz et al., 1991) and a Decagon Ceptometer (Dalla-Tea and Jokela, 1991). These measurements, along with direct measurements of LAI from litterfall and leaf phenologic information, were used to define the extinction coefficient k in Beer-Lambert's equation:

$$I=I_0e^{(-k\cdot LAI/\cos(\theta))} \qquad (2\text{-}13)$$

where I and I_0 are PARs below and above the canopy, respectively, and θ is the solar zenith angle. Considerable temporal variation was found for the k values (Dalla-Tea and Jokela, 1991; Gholz et al., 1991). Daily k values based on projected LAI (not adjusted for zenith angle) varied from 0.54 (June) to 1.16 (December) (Gholz et al., 1991) and 0.52 (June) to 0.97 (December) (Dalla-Tea and Jokela, 1991). The results were sensitive to the selection of the appropriate solar zenith angle for the use of summed daily radiation (Gholz et al., 1991). Some seasonal variation in k was still detected after adjustment for solar zenith angle.

Norman and Jarvis (1975) developed a complex model to describe light transmission and scattering in plant canopies. Simpler models were developed later by empirically fitting the results of this model (Decagon Devices, Inc., 1991). By assuming a spherical leaf angle distribution and random leaf positioning in the canopy, Norman (from Decagon Devices, Inc., 1991) supplied a formula to calculate SAI (the original LAI is changed here to SAI based on Chen and Black (1992b)):

$$SAI = \frac{[f_b\,(1 - \cos\theta) - 1]\ln(I/I_0)}{0.72 - 0.227\,f_b} \tag{2-14}$$

where f_b is the beam fraction, given by:

$$f_b = \frac{I_0 - I_{0d}}{I_0} \tag{2-15}$$

where I_{0d} is the diffuse light measured above the canopy with the sensor shaded.

Radiation transfer in a forest canopy is a very complex process. It often is assumed that foliage is randomly distributed in the canopy. However, in reality this is not the case. Clumping at various levels (i.e., branch, tree, site) always exists. A clumping index or the ratio of silhouette area to total leaf area must be applied for coniferous forests to interpret indirectly measured LAI (Gower and Norman, 1991; Chen and Black, 1991; 1992a). The effect of clumping is more important at the tree scale than at the branch scale (Chen and Black, 1992a).

Rainfall Interception

Interception is the portion of rainfall which cannot reach the ground because of the retention by plant surfaces. It is the difference between gross rainfall and net rainfall (throughfall plus stemflow). Interception is mainly affected by canopy storage capacity and evaporation during rainfall (Horton, 1919; Rutter et al., 1971; 1975; Liu, 1992).

Canopy Storage Capacity

Basically, there are two methods for estimating canopy storage capacity, C_m. The first method is based on the plot of net rainfall (throughfall and stemflow) against bulk rainfall measurements (Leyton et al., 1965; Rutter et al., 1971; 1975) (Figure 2-2). The assumptions behind this method are: (1) the observations along the upper envelope line represent the rainfall events with negligible evaporation during rainfall, and (2) the canopy is fully saturated when rainfall exceeds a minimum value. Most canopy storage capacities have been estimated using this method for predicting interception (e.g. Rutter et al., 1971; 1975; Gash, 1979; Lloyd et al., 1988; Massman, 1983; Hutjes et al., 1990; Lankreijer et al., 1993). Another way to estimate C_m is to multiply LAI and bark area index (BAI) by their specific storage capacity values and sum the products (Herwitz, 1985; Crockford and Richardson, 1990). Specific storage capacity, or the water that can be retained by a unit surface area, is generally determined in the laboratory.

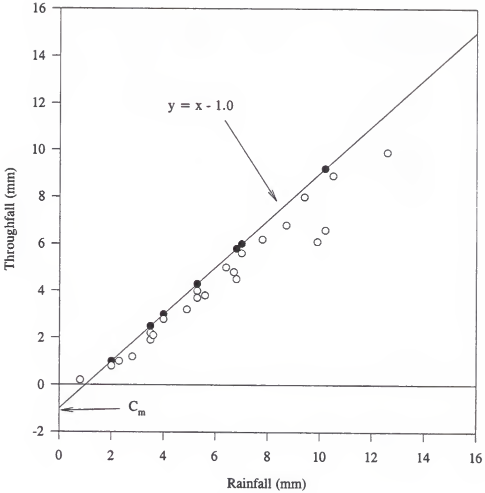


Figure 2-2. Example of the estimation of canopy rainfall capacity C_m using the Leyton method. Solid circles represented the rainfall events without evaporation during rainfall, while open circles indicated that interception was the sum of canopy storage and evaporation from the wet canopy during rainfall.

Evaporation from the Wet Canopy

It has been found that evaporation from a wet canopy may be much faster than just transpiration under the same conditions (Brutsaert, 1982; Shuttleworth, 1989). This could be explained by local or regional advection (Brutsaert, 1982), and no stomatal control when the canopy is wet. The evaporation rate from a wet canopy (during and after rainfall) has been predicted successfully by the Penman-Monteith equation assuming that there is no stomatal resistance (Rutter et al., 1971; 1975; Steward, 1977; Teklehaimanot and Jarvis, 1991). When the canopy is partially wet, a canopy wetness index can be used.

Predictive Models

Much interception data has been collected showing that forest canopy interception accounts for 10-30% of precipitation (Zinke, 1967; Blake, 1975; Webb, 1975). However, interception varies greatly among species, forest density and structure, and under different climatic conditions. Interception can be as high as 50 percent of rainfall in some areas (Calder, 1990). Many predictive models have been developed to predict rainfall interception according to the characteristics of rainfall and canopy. They can be grouped into three categories:

1) Empirical or mathematical models (e.g., Horton, 1919; Merriam, 1960; Leonard, 1965; Czarnowski and Olszewski, 1968; Aston, 1979; Massman, 1980),

2) Stochastic models (e.g., Calder, 1986), and

3) Physical and related models (e.g., Rutter et al., 1971, 1975, 1977; Gash, 1979; Massman, 1983; Liu, 1988; Liu, 1992).

By analyzing interception data sets, Horton (1919) found that interception loss can be described by:

$$I = C_m + e\ t \tag{2-16}$$

where I is event interception, e is evaporation rate during rainfall, and t is rainfall duration. Because storage capacity C_m is not filled during small rainfall events, other equations have been proposed to improve this formula (e.g., Merriam, 1960; Leonard, 1965; Czarnowski and Olszewski, 1968; Aston, 1979; Massman, 1980).

Rutter et al (1971; 1975; 1977) developed a physical model based on the water budget of canopy surfaces. In this model, canopy drainage was described by an empirical function of canopy storage. The model can be described by the continuity equation:

$$\frac{dc}{dt} = (1-p)R - E - k(e^{bc}-1) \tag{2-17}$$

where c is canopy storage, p is the free throughfall coefficient, i.e., the proportion of rain which falls through the canopy without striking a surface, R is precipitation rate, E is evaporation rate of the wet canopy, and k and b are empirical drainage parameters. Massman (1983) changed the drainage function by explicitly including rainfall intensity. Liu (1988) developed a multi-layer interception process model based on the physical processes of forest interception.

Gash (1979) developed a rainfall interception model which is essentially an analytical form of the Rutter model. Because this model was developed for the estimation of interception on an event basis, its data requirement was less intensive than the original

Rutter model. It separated rainfall storms into several categories according to the characteristics of the forest. The total interception during a certain period with n+m rainfall storms is:

$$I = n(1-p-p_t)P_G + (E/R)\sum_{i=1}^{n}(P_i - P_G) + (1-p-p_t)\sum_{j=1}^{m}P_j + q\,S_t + p_t\sum_{k=1}^{m+n-q}P_k \tag{2-18}$$

with

$$P_G = (-R\,C_m/E)\ \ln(1 - \frac{E}{R(1-p-P_t)}) \tag{2-19}$$

where m is the number of rainfall events not sufficient to saturate the canopy completely, n is the number of storms each large enough to saturate the canopy and separated by a sufficient period of time for the canopy to dry, p is the free throughfall coefficient, p_t the proportion of rainfall which is diverted to stemflow, E and R are the average evaporation rate and rainfall intensity corresponding to a saturated canopy, P'_G is the amount of rainfall necessary to saturate the canopy, S_t is the trunk storage capacity, and q is the number of storms with stemflow (rainfall larger than the critical rainfall S_t/p_t). In the application of the Gash model, it often is assumed that all the rain of a day falls in a single storm (e.g., Gash, 1979; Hutjes et al., 1990; Lankreijer et al., 1993).

Mulder (1985) developed a numerical form of the Rutter model. This model did not assume that all daily rain fell in a single storm. Instead, daily rainfall and the number and the duration of storms were used to define an equalized rainfall distribution: the storms are of equal depth and duration, and are evenly spread over the day. The daily averages of the potential evaporation rates for both wet and dry atmospheric conditions were calculated by the Penman-Monteith equation. The data requirement is somewhat between that by the Rutter and Gash models (Lankreijer et al., 1993).

CHAPTER 3
MATERIALS AND METHODS

Study Sites

The study area was located on industrial forest lands of the Georgia-Pacific Corporation at 82°15'W longitude and 29°47'N latitude, about 15 km northeast of Gainesville, Florida (Figure 3-1). The climate was characterized by about 1330 mm annual rainfall, average winter and summer temperatures of 14°C and 27°C, respectively, annual pan evaporation of 1670 mm, and a growing season of 295 days from February 14 to December 6 (Dohrenwend, 1978). The 40 ha study site of a mosaic of slash pine plantations and cypress domes, was in a rather level and poorly-drained interfluvial area. Spodosols (*Ultic Alaquods*) dominated in the pine flatwoods uplands soils with spodic horizons between 30-75 cm depth, and underlain at 100-200 cm by a discontinuous clay layer of variable thickness (Riekerk et al., 1995). Sand-filled karstic depressions with clay at about 200-300 cm depth contained the wetland areas (Riekerk et al., 1995), and had hydric Entisols (*Spodic Psammaquents*) with an average 18 cm thick organic-rich surface layer in the deeper parts. The 30-year old slash pine plantation with a saw palmetto (*Serenoa repens* Bartr.) and gallberry (*Ilex glabra* L. (Gray)) shrub vegetation had a history of prescribed fires and was 5th-row thinned six years ago. Pond cypress, black gum

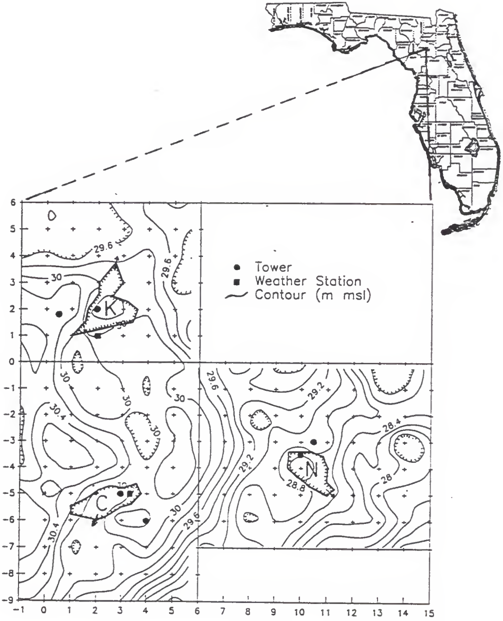


Figure 3-1. Location of the study sites within 50x50 m^2 grid system. C, K and N are wetlands.

(*Nyssa silvatica* var. *biflora*) and swamp bay (*Persea palustris* (Raf.) Sarg.) formed a canopy layer over a ground vegetation of fetter bush (*Leucothoe racemosa* L.), sedges (*Carex walteriana* Bailey), ferns (*Woodwardia virginica* (L.) Smith), and sphagnum moss (*Sphagnum* spp.) in the wetlands (Best and Clayton, 1994).

Three small cypress wetlands, C, K and N, and adjacent pine uplands were selected for detailed hydrologic studies (Figure 3-1). One antenna tower was set up in each wetland and its adjacent pine upland. At least three trees could be reached from each tower for measuring transpiration and stomatal conductance at the leaf level, and the vertical distribution of PAR and LAI.

Ecosystem Structure

Plant Inventory

A 25x25 m plot around the tower in each upland was used for overstory inventory. The location, diameter at breast height (DBH), height, first living branch height, and crown width at the east, west, north and south side of each tree in the plot were measured. A 5-meter-wide transect at the east side of each plot was used for understory sampling.

Twenty percent of each wetland area was sampled using randomly scattered 10x10 m plots to record the species composition, DBH, base diameter, and cypress knee frequency. The importance value of each species was calculated as the average of the relative frequency and basal area. A 5 m wide transect across each wetland was used to measure tree height and its spatial variation.

Overstory Leaf Area Index

Leaf area index and its temporal change were measured directly using phenological and litterfall measurements, and indirectly using a Plant Canopy Analyzer LAI-2000 (Li-Cor, 1989), or a Decagon Ceptometer (Decagon Devices, Inc., 1989) in these stands.

Direct measurements

Phenology was observed from leaf budding to the end of leaf elongation of the three major species, slash pine, cypress and black gum, on a weekly basis. The measured parameters were length and width (or diameter) of leaves/needles. Litterfall was collected monthly using 1x1 m screened traps, sorted by species in the laboratory, dried in an oven at 75 C° for 24 hours and then weighed. The specific leaf area, or the leaf area per unit weight of leaf, was measured when the leaf/needle was mature and fully expanded using fifty "needles" of cypress, and leaves of black gum, or fascicles of slash pine needles. For slash pine, the retention time of needles was assumed to be two years (Gholz et al., 1991).

Indirect measurements

Because instruments for measuring light transmission do not distinguish between light intercepted by foliage and that intercepted by branches and stems, the estimated values should be interpreted therefore as the surface area index or SAI. More exactly, it should be half of SAI (Lang, 1991; Chen and Black, 1992).

Indirect estimates with the LAI-2000 Plant Canopy Analyzer. The LAI-2000 is a portable light sensor system designed to measure diffuse light from several zenith angles simultaneously. The sensor consists of concentric, light detecting rings that receive radiation from different sky sectors centered around the angles 7, 23, 38, 53 and 68 degress from zenith, therefore it senses the diffuse light from a conical region approximately 3.15 tree heights in radius (Li-Cor, 1989). It performs best under uniform overcast weather conditions. However, this kind of condition seldom was present in this area. When operating the LAI-2000, a 90 degree view restrictor was always used to filter the influences of the direct sun beams and of the operator. The above-canopy measurements with the LAI-2000 were taken at the top of the tower. Below-canopy recordings were made directly above each litterfall trap. Because of the relatively large region that is sampled by the LAI-2000, relatively few measurements need to be taken to estimate SAI.

Indirect estimates with the Decagon Ceptometer. The Ceptometer uses a microprocessor and 80 light sensors distributed along a 1-m long probe to measure sunfleck fraction and/or photosynthetically active radiation of both diffuse and direct light. The value displayed by the unit is the average over the length of the probe. The above-canopy data with the Decagon Ceptometer were obtained at the top of the tower. Eighty below-canopy measurements were made at the corners of the litterfall traps with the probe pointing outward along the trap sides at each upland during each visit. In the wetlands, below-canopy readings were taken along a 1-m interval transect across each wetland. Sampling varied from 53 to 72 measurements per visit depending on the size of the wetland.

Radiation penetration and vertical distribution of LAI

The photosynthetically active radiation transfer in individual tree crowns was measured from each tower with the Ceptometer during summer noon when the solar elevation was the highest. When taking the measurements at 1 m vertical intervals, the probe head was held 10 cm away from the trunk and pointed toward it. Photosynthetically active radiation transfer in the canopy of the wetlands and uplands was also measured around the towers under a wide range of solar zenith angles using both the LAI-2000 and the Ceptometer at 1 m vertical intervals. The average of 24 Ceptometer measurements taken at each height interval around the tower was recorded. The vertical distribution of LAI was measured using the LAI-2000, or estimated from the radiation data measured by the Ceptometer using Beer-Lambert's law and Norman's empirical formula (Decagon Devices, Inc., 1991).

Understory Leaf Area Index

Because of the difficulty in monitoring the seasonal variation of LAI of understory species, it was assumed that the evergreen species, gallberry and palmetto, had the same seasonal pattern as pine LAI. The number of palmetto clumps, 'leaf length' (petiole plus leaf blade) of palmetto, and total height of gallberry were measured in a 5x25 m transect, located at the west side of the above mentioned 25x25 plots in the pine plantation. LAI of the understory was calculated with the following empirical equations (Dr. Gholz, personal communication):

Palmetto:

$$leaf\ biomass\ \ (g/frond) = -13.31 + 0.85 \cdot leaf\ length\ \ (cm) \qquad (3\text{-}1)$$

$$leaf\ area\ \ (cm^2/frond) = leaf\ biomass \cdot 62\ \ (cm^2\ g^{-1}) \qquad (3\text{-}2)$$

Gallberry:

$$leaf\ biomass\ \ (g/plant) = 1.29 + 0.087 \cdot total\ Ht\ \ (cm) \qquad (3\text{-}3)$$

$$leaf\ area\ \ (cm^2/plant) = leaf\ biomass \cdot 70\ \ (cm^2\ g\text{-}1) \qquad (3\text{-}4)$$

Palmetto LAI was also estimated by the author by using the assumption of an equitriangular shape for each palmetto leaf.

Wetland understory LAI was measured using the LAI-2000. Ten paired 'above' and 'below' measurements were taken randomly above and below the understory, respectively.

Stomatal Conductance

Field Measurement

Water vapor loss from an individual leaf/needle was measured using a flow-through cuvette porometric system (PP System, 1993). The data were collected from leaf/needle samples under a wide range of conditions (from early morning to late afternoon, sunny and cloudy sky, sunlit and shaded leaves/needles, new and old needles, at different locations in the canopy, etc.) from April 27, 1993, to January 11, 1994. Over 2000 data records (each record includes PAR, air temperature, flow rate of air through the cuvette system, and the relative humidities at the inlet and outlet) were obtained for slash pine and cypress foliage, respectively. The all-sided surface area of pine needles was calculated from the length, diameter and number of needles of a fascicle. It was assumed that each fascicle had a cylindrical form. For cypress trees at these sites, the current-year twig with its knobby leaflets forms an approximate needle. The length and diameter of all leaf/needle samples were measured in the field using a magnifier. The all-sided area of a cypress "needle" was calculated from its length and diameter assuming a cylindrical form.

Leaf conductance (g_l) was calculated from this data using the following equation (McDermitt, 1990):

$$g_l = \frac{u}{s}\frac{e-e_i}{\Delta e} \qquad (3\text{-}5)$$

where u is the flow rate (mol s^{-1}), s is the measured leaf surface area (m^2), e is the vapor pressure of the chamber and outlet air (mbar), e_i is the vapor pressure of the inlet (mbar), and Δe is the leaf-to-air vapor pressure deficit.

Stomatal conductance (g_s) was calculated by (McDermitt, 1990):

$$g_s = \frac{g_l g_b}{g_b - g_l} \qquad (3\text{-}6)$$

where g_b is leaf boundary-layer conductance (mol s^{-1} m^{-2}), which was calculated by (Perrier, 1967, 1976; McDermitt, 1990):

$$g_b = \frac{\rho}{150\sqrt{\frac{w}{u'}}} \qquad (3\text{-}7)$$

where ρ is the mole density of the air (mol m^{-3}), w is the width of the leaf/needle (m), and u' is wind speed (m s^{-1}). For cypress leaves or pine needles, the boundary-layer conductance is about 6 mol m^{-2} s^{-1}, which is much higher than the stomatal conductance.

Transpiration (Tr) was calculated using the following equation (McDermitt, 1990):

$$Tr = \frac{u}{s} \frac{e - e_i}{P} \qquad (3-8)$$

where P is barometric pressure (mbar).

Modeling Stomatal Conductance at the Leaf/Needle Level

The Jarvis (1976) model, which assumed that all environmental variables were affecting g_s at the same time, was calibrated first with the g_s data as measured for both species. Some models based on only one or two environmental factors at particular points of time to predict g_s were then compared against the calibrated Jarvis model. The assumption behind the one-factor scheme (MIN11 and MIN12) was that there was a single strongest controlling factor that affected g_s at any point of time, and that the effects of other factors were masked by that factor. The two-factor scheme (MIN21 and MIN22) was based on a similar assumption except that two factors were assumed to work together to control g_s at any point of time. In addition, multiple regression models were developed to relate g_s to PAR, VPD, air temperature (T) , and various transformations and combinations of these variables using a forward stepwise selection method (SAS Institute Inc., 1989).

The formulation of the selected g_s models was as follows:

1. *LIN* (*Multiple linear regression model*):
   $g_s = a_0 + a_1 PAR + a_2 VPD + a_3 T$
2. *NLIN* (*Multiple nonlinear regression model*):
   $g_s = a_0 + f(PAR, VPD, T)$
3. *Jarvis*:
   $g_s = g_0 f_1(PAR) f_2(VPD) f_3(T)$
4. *MIN11*:
   $$g_s = g_0 \min(f_1(PAR), f_2(VPD), f_3(T)) \tag{3-9}$$
5. *MIN21*:
   $g_s = g_0 \min(f_1 f_2, f_2 f_3, f_1 f_3)$
6. *Jarvis'*:
   $g_s = g_0 f_4(PAR) f_2(VPD) f_3(T)$
7. *MIN12*:
   $g_s = g_0 \min(f_4(PAR), f_2(VPD), f_3(T))$
8. *MIN22*:
   $g_s = g_0 \min(f_4 f_2, f_2 f_3, f_4 f_3)$

where g_0 is the maximum g_s, a_0, a_1, a_2 and a_3 are regression coefficients, and f1(PAR), $f_2(VPD)$, $f_3(T)$ and $f_4(PAR)$ are scaling functions of PAR, VPD and T, respectively. They take these forms (e.g., Jarvis, 1976; Massman and Kaufmann, 1991):

$$
\begin{aligned}
f_1(PAR) &= \frac{PAR}{b_0 + PAR} \\
f_2(VPD) &= \frac{g_m}{g_0} + \left(1 - \frac{g_m}{g_0}\right) e^{-c_0 VPD} \\
f_3(T) &= \begin{cases} (1+s_1(T_0-T))^{-1} & \text{if } T<T_0 \\ (1+s_2(T-T_0))^{-1} & \text{if } T\geq T_0 \end{cases} \\
f_4(PAR) &= \frac{PAR}{\dfrac{b_0}{1.001-f_2(VPD)} + PAR}
\end{aligned}
\tag{3-10}
$$

where b_0 is the Michaelis-Menton coefficient, which represents the PAR when g_s equals $g_0/2$, T_0 is the optimum air temperature for stomatal functioning, g_m is the minimum g_s, and c_0, s_1 and s_2 are optimized coefficients. The values of these scaling functions range from 0 to 1. The introduction of $f_4(PAR)$ is based on the following consideration. Measurements of g_s obtained in the field represent only a subset of the total potential g_s. For example, some data, such as the conductance corresponding to a very low VPD and very high PAR, seldom can be obtained under field conditions. However, these values may form quite a different asymptotic boundary line in the relationship between g_s and PAR. In order to account for this phenomenon, the Michaelis-Menton coefficient, b_0, was assumed to vary with VPD, which in turn affected the asymptotic boundary line. The use of the constant 1.001 instead of 1 was to protect the equation from going to infinity. The model parameters were determined using optimization techniques (SAS Institute Inc., 1989).

Measurement of Rainfall Interception

Storage Capacity

The specific storage capacities of leaves, branches and stems were determined in the laboratory. Samples of these entities were taken from trees after a long dry period (>5 days). Woody samples were sealed with melted wax at each end in the field. All samples were stored in a cooler, and transported immediately to the laboratory for the following measurements:

Leaves/needles

Water retained on the surface of leaves/ needles is the difference between wet and dry leaves/needles. Specific storage capacity is the amount of water retained divided by the all-sided surface area of the sample. After measuring the fresh weight, the leaves/needles were soaked in water for 10 seconds. The droplet at the tip of the leaf/needle was removed with a filter paper before measuring the wet weight. The surface area of the leaf/needle sample was determined as before.

Branches and stems

The initial dry weight was obtained by measuring the fresh samples. The samples were then soaked in water and weighed periodically until the weights did not change much between each consecutive measuring interval. Thereafter, the samples were dried in the air and weighed periodically to determine the drying rates of the retained water down to nearly steady state. The specific storage capacity was then determined by dividing the surface-retained water by the total surface area.The determination of rainfall retention capacity of branches and stems is illustrated in Figure 3-2. The bark portion of the stem was saturated after being soaked in water for about one hour. The continuous constant increase in weight thereafter (linear portion) was probably caused by water infiltration from the bark to the xylem, which was not considered to be part of surface retention. The drying process indicated that the water retained by the bark evaporated faster than water from the xylem. Average retention capacity (C_m) was the difference between two parallel straight lines: the upper line was determined by the portion of constant increase in weight, and the lower line ran from the beginning point of the wetting process to the turning point of the evaporation process.

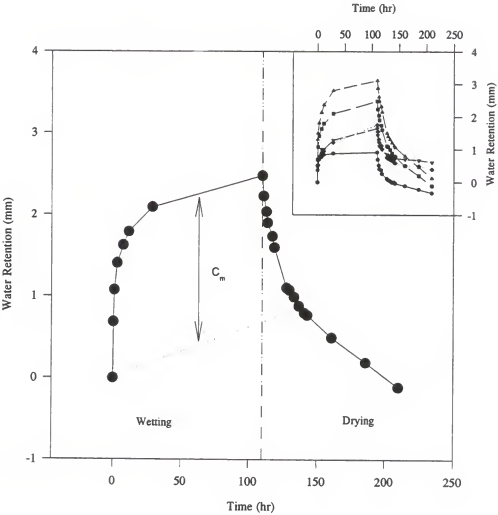


Figure 3-2. Determination of rainfall retention capacity by wetting and drying branches and stems in the laboratory. Insert shows that all the stems demonstrated similar wetting and drying processes.

Canopy storage capacity

The storage capacities of leaves, branches and stems at the canopy level were estimated from the specific storage capacity, and the surface area index of these entities in the canopy. Stem area index can be estimated effectively based on the assumption of a conical surface for each trunk (one-half basal circumference times tree height) (Whittaker and Woodwell, 1967; Swank and Schreuder, 1974). Branch surface area index can be estimated from allometric growth relationships (Whittaker and Woodwell, 1967; Brown, 1978).

Rainfall Interception

One rainfall gauge was set up in a canopy gap near each pair of cypress and slash pine plots. Rainfall and throughfall were measured on weekly basis from April 1, 1992, to March 31, 1993. Ten 100x7.5 cm^2 throughfall collectors (made from PVC pipes cut lengthwise in half) were installed about 0.7 m away from the east side of the litterfall trap in each plot. The locations of trees, tower, litterfall traps and throughfall troughs in the upland plots are shown in Figures 3-3, 3-4 and 3-5. Stemflow was not measured in this study becuase it accounts only for about 3 percent of gross rainfall in these ecosystems (Heimburg, 1984; Allen and Gholz, 1995). However, in calculating interception, it was assumed that when gross rainfall was more than 5 mm, stemflow would account for 3 percent of gross rainfall. Otherwise, there would be no stemflow:

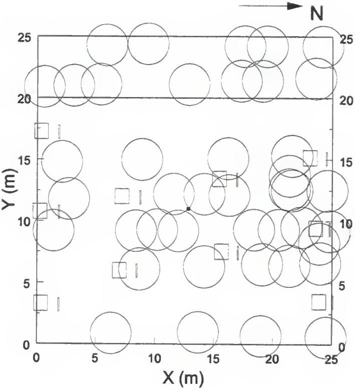


Figure 3-3. Map of trees (O), tower (■), littertraps (□) and throughfall troughs (❙) in the C upland plot.

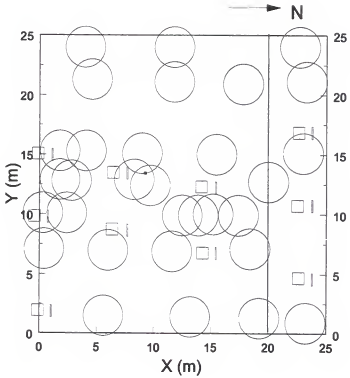


Figure 3-4. Map of trees (O), tower (■), littertraps (□) and throughfall troughs (▮) in the K upland plot.

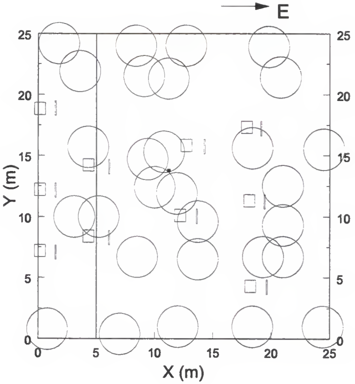


Figure 3-5. Map of trees (O), tower (■), litter traps (□) and throughfall troughs (▮) in the N upland plot.

If R > 5 mm then

$$I = R - Th - 0.03R \tag{3-11}$$

else

$$I = R - Th \tag{3-12}$$

where I is rainfall interception, R is rainfall, and Th is throughfall.

Evaporation From Standing Water in Wetlands

A floating standard class-A evaporation pan was installed in each wetland and the water level change measured on a weekly basis to estimate the evaporation of standing water in wetlands. The average measured throughfall depth of rainfall events was subtracted from the measured water level change to determine the actual evaporation from the water surface.

At the same time, the fluctuation of water levels in the wetlands was continuously monitored using Stevens water table recorders. A water level was measured once at each grid point of the 10x10 m grid system to determine the wetland bottom topography, and therefore the relationship between water level and the fraction of wetland covered by standing water. The actual evaporation from the wetlands was the evaporation as measured by the floating pan, but weighted by the water surface area fraction. In this study, the boundary of a wetland was determined as the palmetto line.

Soil Moisture Content

Volumetric soil moisture content (θ) was measured periodically using time-domain reflectometry (TDR) (Topp et al., 1980; Topp and Davis, 1985; Nadler et al., 1991; Whalley, 1993). To determine θ by the TDR method, a TDR cable tester was used to measure the apparent length *l* of a set of metal probes embedded in the soil with an actual length L. Then θ was determined by the general empirical equation (Topp et al., 1980):

$$\theta = -0.053 + 0.0292\,k - 0.00055\,k^2 + 0.0000043\,k^3 \qquad (3\text{-}13)$$

where

$$k = \left(\frac{l}{L}\right)^2$$

Probes with a length of 0.1, 0.2, 0.3, 0.4 and 0.8 m were used to measure the θ profile down to 0.8 m in depth at 0.1 m intervals at more than 100 locations in the slash pine uplands in order to define as much as possible the spatial variability of θ. Volumetric water content when measured below the ground water table was considered to be the porosity of the soil at that depth.

Estimation of ET from Water Level Fluctuations

The specific yield of an ecosystem (water release per unit drop in water level) is crucial to the estimation of ET from water level fluctuations in both wetlands and uplands.

Specific Yield

The specific yield of a wetland (S_y) changes with water depth or the extent of standing water in it. The S_y varies between S_{yw} (=1), the specific yield when the standing water covers the whole wetland, and the specific yield S_{ys} of the bottom soil when the water table is at or below the lowest point of the wetland. S_y is the sum of the specific yield of the standing water and of the wetland soil area weighted by their fractions of the covered area:

$$\begin{aligned} S_y &= f_w S_{yw} + (1 - f_w) S_{ys} \\ &= f_w (1 - S_{ys}) + S_{ys} \end{aligned} \qquad (3\text{-}14)$$

where f_w is the area fraction of the water surface in the wetland. It can be seen that S_y is a linear function of water surface fraction f_w with a slope of $1 - S_{ys}$ and an intercept of S_{ys}. In addition, the following relations hold:

1) $S_y = S_{yw} = 1$, when $f_w = 1$;

2) $S_y = S_{ys}$, when $f_w = 0$;

3) $S_{ys} < S_y < 1$, when $0 < f_w < 1$.

The effect of the cross sectional area occupied by stems and knees is negligible in wetlands, because the area of stems and knees is usually less than 100 m^2 ha^{-1} (basal area is often about 50 m^2 ha^{-1}) or 1 percent of the wetland area.

Equation (3-14) shows that when the specific yield S_{ys} of the soil in the wetland is assumed to be zero or not considered (e.g., Ewel and Smith, 1992), the estimated specific yield of the wetland S_y is lower than the actual by a difference of $(1 - f_w)S_{ys}$. The smaller the area covered by standing water, the larger the difference. The underestimation of S_y is also dependent on the specific yield of the soil S_{ys}. The difference increases with the increase of S_{ys}. If an average f_w of 0.5 and a S_{ys} of 0.2 mm mm^{-1} are assumed, the underestimation of S_y of the wetland would be 0.1 mm mm^{-1} or 17 percent. If f_w averaged 0.3, the underestimation of S_y would be 0.14 mm mm^{-1} or 32 percent.

The specific yield of a wetland is determined solely by the wetland soil when there is no standing water in the wetland. The determination of S_y then is similar to that of uplands. In uplands, the specific yield is considered to be the same as the specific soil moisture change (soil moisture change per unit drop in water table).

Estimating Evapotranspiration

Basically, three methods can be used to estimate ET in wetlands based on the White (1931) method (Eq. 2-1).

Method I

ET is estimated from the water loss corresponding to the water level drop due to ET in the wetland. S_y is estimated using Eq. (3-14).

Method II

ET is estimated from water released only from the part of the wetland covered by standing water, where $S_y = S_{yw} = 1$. The assumption is that water withdrawn by trees growing in standing water from the surrounding soil zone equals that withdrawn by trees growing in the surrounding soil zone from the standing water area. In other words, the water level drop due to ET (in depth) in the area with standing water represents the ET (in depth) in the whole wetland.

Method III

ET is estimated from water loss from the part of the wetland that is covered by standing water with $S_y = S_{yw} = 1$. The difference between this method and method II is in the use of the weighting area. Method III divides the water loss (in volume) by the delineated wetland area, while method II only by the standing water area. Actually, S_y is estimated by not considering the contribution from the soil portion in method III (different from method I). This method has been used previously to estimate ET from three cypress swamps (Ewel and Smith, 1992).

It should be noted that the application of methods I and III involves the use of the relationship between water level and the corresponding water surface in the wetland, which is not easy to obtain accurately and therefore introduces some uncertainty. There is no need to know this relationship for method II.

Special attention should be paid to the estimation of annual ET from the daily estimates based on the three methods described above. It is by assuming that interception loss equals the ET under the same conditions without rainfall (usually a good assumption), the annual ET could be estimated as the product of average daily ET and the number of days in a year. Annual ET could not be estimated as the sum of interception and the product of the average daily ET and the number of days in a year. This consideration should be adequate for both wetlands and uplands as long as ET is estimated from water table fluctuations.

The resolution of the hydrographs was not high enough to be used in any of the three methods because of the water level recorders that were used in the three wetlands of this study,. In order to test the effectiveness of these methods and the consistency with the modeling results, only method II was used to estimate ET from a wetland in the Bradford forest (Riekerk, 1989). The other two methods were not tested because of the lack of data for the relationship between water level and water surface area in this particular wetland.

Statistical Analysis

The statistical ANOVA procedure (SAS, 1989) was used to see if there was any significant difference between cypress and slash pine in terms of stomatal conductance and transpiration at the leaf/needle level. The comparison between species was restricted to the data obtained during the growing season, because the cypress is deciduous.

The T-test with unequal variances was used to test the following null hypotheses based on the eighteen plot-year simulation results (six plots and three years):

There are no differences between cypress wetlands and slash pine uplands in terms of:

(1) transpiration,

(2) rainfall interception,

(3) evaporation from substrate, and

(4) evapotranspiration.

Development of An Evapotranspiration Model

The structure of the evapotranspiration model (ETM) is illustrated in Figure 3-6. The submodels of rainfall interception, transpiration, and evaporation from the water surfaces in wetlands or from the forest floor will be described in detail in this section. The computer code in Qbasic and the format of input and output data are illustrated in the Appendices.

Derivation of a New Interception Model

Canopy dryness and storage

As canopy dryness index (D) is a measure of the saturation of the canopy storage capacity (C_m, mm), it can be defined as

$$D=1-C/C_m \tag{3-15}$$

where C is actual canopy storage (mm). For the purpose of simplicity, the concept of canopy storage used here is somewhat different from that of Rutter and others (Rutter et al., 1971; Massman, 1983). In Rutter's model, canopy storage can be temporarily more than the storage capacity C_m during rainfall storms. However, this excess portion of the storage will eventually drain from the canopy as throughfall or stemflow (Rutter et al., 1971; Massman, 1983). Therefore, canopy storage is defined here as rainfall retained on the canopy that will not drain from the canopy to the ground. The only pathway for loss from canopy storage is by evaporation during and after rainfall. With this definition, the canopy dryness index does not go negative.

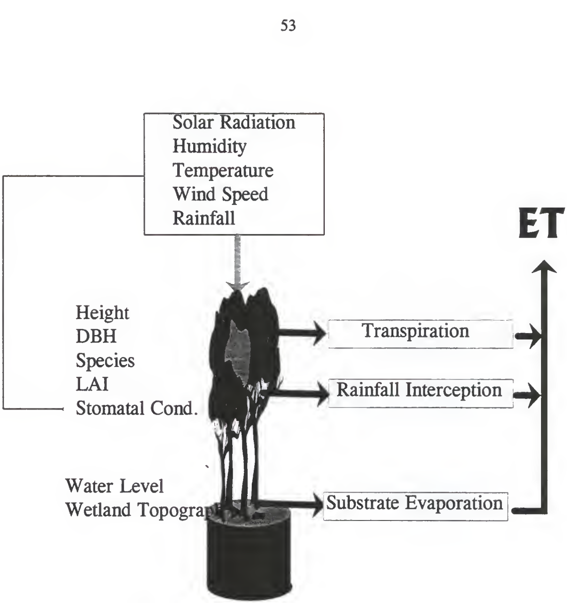


Figure 3-6. The structure of the evapotranspiration model ETM.

In order to obtain the equations for canopy dryness index and storage with respect to stand characteristics and rainfall, the change of rainfall through the canopy will be examined first. As rain falls through a canopy, it will be intercepted in part. The change of rainfall (ΔP) after passing through the canopy is proportional to rainfall intensity (R), canopy dryness index (D) and the time interval (Δt), that is:

$$\Delta P = k * R * D * \Delta T \tag{3-16}$$

where k is a proportionality factor that will be determined later.

At the same time, the change in canopy storage is

$$\Delta C = \Delta D * C_m \tag{3-17}$$

The evaporation of intercepted water can be neglected if the time interval is short. . Therefore, the change of rainfall after passing through the canopy equals the change in canopy storage. By rearranging Eqs (3-16) and (3-17) and integrating, we obtain:

$$D = D_0 * \exp(-kP/C_m) \tag{3-18}$$

or

$$D = \exp(-k(P_0 + P)/C_m) \tag{3-19}$$

where D_0 is the canopy dryness index before the rainfall P, and P_0 the amount of rainfall from the previous event that is associated with D_0. From equation (3-18) we can see that if the time between two consecutive rainfall events is enough to evaporate all the intercepted water held by the canopy ($D_0=1$), there would be no carry-over effect from the former rainfall event to the next. Otherwise, the former rainfall event would have an effect on the next event, which is reflected by the canopy dryness index ($D_0 < 1$), or the associated amount of rainfall ($P_0 > 0$) from the last event.

Rainfall stored as new canopy storage (C') during a rainfall event is the difference between total canopy storage (C) and the antecedent storage just before the rainfall (C_0), i.e.:

$$C' = C - C_0 \tag{3-20}$$

or

$$C' = C_m D_0 [1-\exp(-kP/C_m)] \tag{3-21}$$

Evaporation of intercepted rainfall during rainfall

We assume that a certain volume of water retained in the canopy could saturate a certain surface area. Therefore, the following relationship exists:

$$C/C_m = SAI_w/SAI \tag{3-22}$$

where SAI and SAI_w are total surface area index and wet surface area index, respectively. From Eq (3-15) and (3-18), we obtain canopy storage at any time during rainfall:

$$C = C_m(1-D_0\exp(-kP/C_m)) \tag{3-23}$$

Substituting Eq (3-23) into (3-22), we obtain the wet surface area at any time during rainfall:

$$SAI_w = SAI \cdot [1-D_0 \exp(-kP/C_m)] \qquad (3\text{-}24)$$

From Eq (3-24), we can see that the following relationships hold:

$SAI_w = (1-D_0)*SAI$ when $P=0$

$SAI_w = SAI$ when $D_0=0$

This describes what we have seen in reality.

Total evaporation (E) during a storm is the integral of the evaporation rate from the canopy over the total rainfall time T, i.e.:

$$E=\int^{T} e_w dt \qquad (3\text{-}25)$$

where e_w is evaporation rate from the canopy. Substituting Eq (3-24) into (3-25) and considering that e_w is the product of the evaporation rate (e) of the canopy when it is fully wet and the wetness index of the canopy (1-D), we have:

$$E=\int^{T} (1-D) \cdot e \cdot dt \qquad (3\text{-}26)$$

or

$$E=\int^{T} e \cdot [1-D_0 \exp(-kP/C_m)] \cdot dt \qquad (3\text{-}27)$$

As a result, evaporation of intercepted water during rainfall is determined by the evaporation rate of the canopy (as determined by the total surface area index and environmental variables), canopy dryness before rainfall, amount and duration of rainfall, canopy storage capacity and a proportionality factor k.

Rainfall interception

The above equations for canopy dryness index, canopy storage, and evaporation during rainfall contained the unknown factor k. Optimization methods could be used to obtain it from observations by treating all these formulas as empirical. However, without a biological or physical explanation, the application of these kinds of formulations will be restricted. The following derivation shows that k represents the ground coverage.

The differential equation of canopy storage with respect to rainfall may be derived from Eq. (3-23):

$$\frac{dC}{dt}=k\cdot D_0\cdot \exp\left(-kP/C_m\right) \qquad (3\text{-}28)$$

It is apparent that when $P_0=0$, and P approaches zero, then the following expression holds:

$$\frac{dC}{dP}\rightarrow k \qquad (3\text{-}29)$$

On the other hand, from the water budget of the canopy, canopy storage is:

$$C=P-Th-Sf-E \qquad (3\text{-}30)$$

where Th and Sf are throughfall and stemflow respectively. Generally, throughfall and stemflow have linear relationships with rainfall. Including these relationships into Eq. (3-30), we have:

$$C=P-(a_t+b_t \cdot P)-(a_s+b_s \cdot P)-E \qquad (3\text{-}31)$$

where a_t, b_t, a_s, b_s are the regression coefficients of throughfall and stemflow with rainfall, respectively. Therefore another expression for the differential equation of canopy storage with respect to rainfall is:

$$\frac{dC}{dP}=1-b_t-b_s-\frac{dE}{dP} \qquad (3\text{-}32)$$

When P approaches zero, then $b_t \to b_0$, $b_s \to 0$, and $dE/dP \to 0$, and we have:

$$\frac{dC}{dP} \to 1-b_0 \qquad (3\text{-}33)$$

where b_0 usually is called the free throughfall coefficient (Gash, 1979; Rutter et al., 1971; Aston, 1979), or canopy gap fraction. It is obvious that $1-b_0$ is an index of ground coverage, the ratio of vertically-projected vegetation surface area to ground area (ranging from 0 to 1).

The general expression for k derives from Eq. (3-29) and (3-33):

$$k=1-b_0 \qquad (3\text{-}34)$$

so k represents ground coverage and is a measurable parameter.

Total interception is the sum of the change in canopy storage and evaporation during rainfall and can be described fully by:

$$I = C_m \cdot D_0 \cdot [1-\exp(-(1-b_0)P/C_m)] + \int^{T} e \cdot [1-D_0 \exp(-(1-b_0)P/C_m)] \cdot dt \qquad (3\text{-}35)$$

or

$$I=C_m*(D_0-D)+\int^T(1-D)*e*dt \tag{3-36}$$

There are no empirical parameters in this model. The evaporation rate can be predicted by using the Penman-Monteith combination equation by assuming no stomatal resistance in a wet canopy (e.g., Rutter, 1971; 1975; Shuttleworth, 1989):

$$E=\frac{\varepsilon(R_n-G)+\rho c_p D_a g_a/\gamma}{(\varepsilon+1)\lambda} \tag{3-37}$$

Canopy dryness index during inter-event periods

So far, an interception model based on the interception process of the forest canopy has been developed. It has been shown that both canopy dryness index before and during rainfall are important to interception loss. The dynamics of canopy dryness index during inter-event dry periods will be considered next.

During this inter-event dry period, the loss rate of canopy storage is determined by the evaporation rate of the canopy:

$$C_1-C_2=e_d*(1-D)*dt \tag{3-38}$$

where C_1 and C_2 are the canopy storages at the beginning and end of the time interval dt, 1-D is the canopy wetness index at the beginning of the time period dt, and e_d is the evaporation rate of the wet canopy after rainfall. Substituting $C_1=(1-D)*C_m$ and $C_2=(1-D-dD)*C_m$ into (3-38) results in the following:

$$\frac{dD}{1-D}=\frac{e_d}{C_m}dt \qquad (3\text{-}39)$$

So by integration the canopy dryness index at any time becomes:

$$D=1-(1-D_0)\cdot\exp(e_d\cdot T/C_m) \qquad (3\text{-}40)$$

where D_0 is the initial canopy dryness index of the time interval T.

Analytical form of the new interception model

It is interesting to see if the above interception model can be simplified based on some reasonable assumptions. Equation (3-32) shows that when canopy storage capacity is saturated, e.g. dC/dP=0, the rate of change of evaporation with respect to rainfall intensity is:

$$dE/dP=1-b_t-b_s \qquad (3\text{-}41)$$

Therefore, the *average* evaporation rate ($\bar{e}$) of a wetted canopy during rainfall is related to the *average* rainfall intensity by:

$$\bar{e}=(1-b_t-b_s)\cdot\bar{R} \qquad (3\text{-}42)$$

Substituting equation (3-42) into (3-35) results in a simplified form of the interception model:

$$I = C_m\cdot(D_0-D)\,[1-(1-b_0)\,\bar{e}/\bar{R}] + \bar{e}\cdot T \qquad (3\text{-}43)$$

When $D_0 = 1$, or the canopy is dry before each rainfall event, the interception model becomes:

$$I = C_m \cdot [1 - \exp(-(1-b_0)P/C_m)][1-(1-b_0)\overline{e}/\overline{R}] + \overline{e} \cdot T \qquad (3\text{-}44)$$

If there are n rainfall events over a certain period of time, then the total interception I_t would be:

$$\begin{aligned} I_t &= C_m \cdot [1-(1-b_0)\frac{\overline{e}}{\overline{R}}][n - \sum_{i=1}^{n} \exp(-(1-b_0)P_i/C_m)] + \frac{\overline{e}}{\overline{R}} \sum_{i=1}^{n} P_i \\ &= C_m \cdot [1-(1-b_0)\frac{\overline{e}}{\overline{R}}][n - \sum_{i=1}^{n} D_i] + \frac{\overline{e}}{\overline{R}} \sum_{i=1}^{n} P_i \end{aligned} \qquad (3\text{-}45)$$

where D_i is the canopy dryness index after rainfall event *i* with rainfall P_i and duration T_i.

Transpiration Models

General combination equation

Using the basic equations originally devised by Waggoner and Reifsnyder (1968) and an electrical analogue where latent heat flux replaced current and the driving potential was $(\rho^* c_p/\gamma)e$ (where e is vapor pressure, Figure 3-7), Lhomme (1988a) developed a general combination equation (GCE) for the total latent heat flux from a canopy

$$\lambda E = \frac{\Delta(Rn-S) + \rho c_p (VPD + \Delta\delta Te) g'_a}{\Delta + \gamma(1 + g'_a/g'_s)} \qquad (3\text{-}46)$$

where Δ is the slope of the saturated vapor pressure curve (Pa K^{-1}), Rn is the net radiation above the canopy (W m^{-2}), S is soil heat flux density (W m^{-2}), ρ is air density (kg m^{-3}), c_p is specific heat of the air at constant pressure (J kg^{-1} K^{-1}), VPD is the vapor pressure

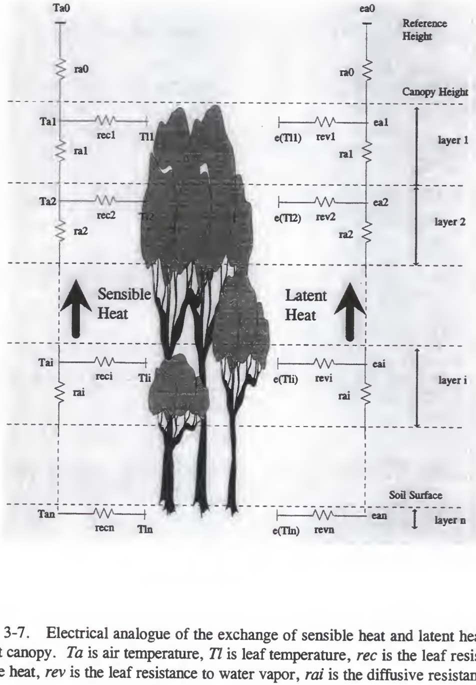


Figure 3-7. Electrical analogue of the exchange of sensible heat and latent heat within a forest canopy. *Ta* is air temperature, *Tl* is leaf temperature, *rec* is the leaf resistance to sensible heat, *rev* is the leaf resistance to water vapor, *rai* is the diffusive resistance when crossing layer *i*, *e(Tl)* is the saturated water vapor pressure at leaf temperature, *ea* is the vapor pressure in the air, and *Ta0* and *ea0* is the air temperature and vapor pressure at the reference height.

difference of the air at the reference height above the canopy (Pa), γ is psychrometric constant (66 Pa K^{-1}), δTe is the difference of the canopy equivalent temperatures for sensible heat transfer Te_c and for latent heat transfer Te_v (see Lhomme (1988b) for definitions and discussion), and g'_a and g'_c are the bulk stomatal canopy conductance and the bulk aerodynamic conductance, respectively. These conductances are defined by:

$$g'_c = \frac{1}{rc_v - rc_c} \qquad (3\text{-}47)$$

$$g'_a = \frac{1}{ra_0 + rc_c} \qquad (3\text{-}48)$$

where ra_0 is the aerodynamic resistance (reciprocal of a conductance) between the top of the canopy and the reference height, rc_v and rc_c are the canopy resistances to latent and sensible heat transfer, respectively, with the definitions:

$$rc_c = \frac{(1 + ra_1 B_c)}{A_c} \qquad (3\text{-}49)$$

$$rc_v = \frac{(1 + ra_1 B_v)}{A_v} \qquad (3\text{-}50)$$

where A_x and B_x (x=c or v) are defined as:

$$A_x = \sum_{i=1}^{n} \alpha_{x,i}\, ge_{x,i} \qquad (3\text{-}51)$$

$$B_x = \sum_{i=1}^{n} \beta_{x,i}\, ge_{x,i} \qquad (3\text{-}52)$$

where $ge_{v,i}$ and $ge_{c,i}$ are the horizontal conductances for latent heat (leaf conductance) and sensible heat (leaf boundary-layer conductance) transfer in layer *i*:

$$ge_{c,i} = LAI_i \, gb_i \qquad (3\text{-}53)$$

$$ge_{v,i} = LAI_i \, \frac{gs_i \, gb_i}{gs_i + gb_i}$$

where LAI_i is the leaf area index in the *i*th layer, and gs_i and gb_i are the stomatal conductance and leaf boundary layer conductance, respectively, of a unit LAI in layer *i*.

The intermediate variables are calculated by:

$$\alpha_{x,i-1} = a_{x,i}\alpha_{x,i} + b_{x,i}\alpha_{x,i-1} \qquad (3\text{-}55)$$

$$\beta_{x,i-1} = a_{x,i}\beta_{x,i} + b_{x,i}\beta_{x,i-1} \qquad (3\text{-}56)$$

$$\varepsilon^{j<i-1}_{x,i-1} = a_{x,i}\varepsilon^{j}_{x,i} + b_{x,i}\varepsilon^{j}_{x,i-1} \qquad (3\text{-}57)$$

$$\varepsilon^{i-1}_{x,i-1} = a_{x,i}\varepsilon^{i-1}_{x,i} = a_{x,i}c_{x,i-1} \qquad (3\text{-}58)$$

$$\varepsilon^{i}_{x,i-1} = c_{x,i} \qquad (3\text{-}59)$$

with

$$a_{x,i} = 1 - b_{x,i} - c_{x,i} \qquad (3\text{-}60)$$

$$b_{x,i} = -\frac{ga_{i-1}}{ga_i} \qquad (3\text{-}61)$$

$$c_{x,i} = -\frac{ge_{x,i}}{ga_i}$$

with the first coefficients being defined as:

$$\begin{aligned} \alpha_{x,1} &= 1 \\ \alpha_{x,2} &= 1 - c_{x,1} \\ \beta_{x,1} &= 0 \\ \beta_{x,2} &= 1 \\ e^{1}_{x,2} &= c_{x1} \end{aligned} \tag{3-63}$$

The vertical diffusive conductance ga_i , when vertical flux of latent heat crosses layer *i*, is calculated based on the eddy diffusivity K(z) in layer *i*:

$$ga_i = [\int_{z_i}^{z_{i-1}} \frac{dz}{K(z)}]^{-1} = \frac{K_i}{z_{i-1} - z_i} \tag{3-64}$$

where K_i is the mean eddy diffusivity for heat and vapor for layer i ($m^2\ s^{-1}$).

Multi-layer Penman-Monteith equation

Total transpiration for the forest canopy (Tr) was estimated by application of the Penman-Monteith equation to each layer of the canopy (MPM):

$$Tr = \frac{1}{\lambda} \sum_{i=1}^{n} \frac{\varepsilon (R_{n,i-1} - R_{n,i}) + c_p\ \rho\ VPD\ g_{b,i}/\gamma}{\varepsilon + 1 + g_{b,i}/g_{c,i}} \tag{3-65}$$

where n is the number of layers. It is assumed that the top layer is the first layer. The leaf boundary layer conductance in layer i is $g_{b,i}$, which is estimated in the same way as in GCE. The stomatal conductance in layer i is $g_{c,i}$, which is estimated by:

$$g_{c,i} = \sum_{j=1}^{k} gs_{i,j}\ LAI_{i,j} \tag{3-66}$$

where $gs_{i,j}$ and $LAI_{i,j}$ are stomatal conductance and leaf area index of species j in layer i, and k is the number of species in layer i.

Energy and turbulence transfer in a forest canopy

The Beer-Lambert law was used to describe the profiles of net radiation Rn(z) and PAR in the canopy:

$$Rn(z) = Rn(z_h)\, e^{-k\frac{SAI(z)}{2\cos\theta}} \qquad (3\text{-}67)$$

and

$$PAR(z) = PAR(z_h)\, e^{-k\frac{SAI(z)}{2\cos\theta}} \qquad (3\text{-}68)$$

where d θ is the solar zenith angle, and SAI(z) is cumulative surface area index from canopy top z_h to the height z. The extinction coefficient k value of 0.35 corresponding to the half-SAI was derived from radiation measurements (see Chapter 4). If converted to total SAI, it would have been 0.175, which was very close to the value of 0.15 (or $0.468/\pi$) used by Cropper and Gholz (1993).

The profiles of wind speed u(z), turbulent diffusivity K(z) and boundary-layer resistance rb(z) have been taken from Perrier (1967, 1976):

$$u(z)=u(z_h)\, e^{-b_0 L(z)} \qquad (3\text{-}69)$$

$$K(z)=[a_0/l(z)^2]\,\frac{du(z)}{dz} \qquad (3\text{-}70)$$

$$gb(z) = \frac{1}{\alpha}\left(\frac{u(z)}{w}\right)^{\beta} \tag{3-71}$$

where w is the width of a leaf (m), the theoretically derived coefficients a_0 and b_0 are 0.4 and 0.6, respectively, α and β are 150 and 0.5 respectively, l(z) is the leaf area density or leaf area per unit volume (m^2 m^{-3}), and L(z) is the cumulative leaf area index (m^2 m^{-2}) related to leaf area density by:

$$L(z) = \int_{z}^{z_h} l(z)\,dz \tag{3-72}$$

Aerodynamic conductance g_a from $(d+z_0)$ to the reference height z was calculated by (Monteith, 1965; Thom, 1975; Brutsaert, 1992; Calder, 1990):

$$\begin{aligned} g_a &= \frac{u_*^2}{u(z)} \\ &= \frac{k^2 u(z)}{\ln^2((z-d)/z_0)} \end{aligned} \tag{3-73}$$

where d is displacement height (m), z_0 is roughness length (m), k is the von Karman's constant (0.41), z is a reference level above the canopy (m), u(z) is the wind speed at level z (m s^{-1}) (see Figure 2-1), and u_* is the friction velocity (m s^{-1}), which can be interpreted physically as an index of the rate of rotation of the frictionally driven eddies in the air flow above the surface (Thom, 1975). The displacement height and roughness length are commonly related to stand height (e.g., Webb, 1975; Brutsaert, 1982; Shuttleworth, 1989). It has been shown that these parameters depend quite strongly on both height and density of the vegetation and can be expressed as a function of LAI and canopy height (H) (Shaw and Pereira, 1982; Lindroth, 1993):

$$d=(0.858-0.408\,e^{-0.328LAI})\,H \tag{3-74}$$

and

$$z_0=(0.051+0.096\,e^{-0.611LAI})\,H \tag{3-75}$$

Aerodynamic conductance between the canopy top height H and the reference height z is calculated by (Lhomme, 1991):

$$ga_0=\frac{k\ u_*}{\ln\left(\frac{z-d}{H-d}\right)} \tag{3-76}$$

Degree of coupling between the canopy and the atmosphere

The formula for calculating the decoupling coefficient Ω was derived from the energy and aerodynamic combination method (Jarvis and McNaughton, 1986; Martin, 1989; Pinty et al., 1992) as:

$$\Omega=\frac{\varepsilon+\chi}{\varepsilon+\chi\,(1+g_b/g_c)} \tag{3-77}$$

with

$$\chi=1+\frac{BAI}{LAI}+\frac{g_r}{g_c} \tag{3-78}$$

where g_c is canopy stomatal conductance (mol $m^{-2}\,s^{-1}$), g_b is boundary conductance (mol

m^{-2} s^{-1}) and BAI is the bark area index (m^2 m^{-2}), and g_r (mol m^{-2} s^{-1}) is the conductance of sensible heat transfer:

$$g_r = \frac{4\sigma' T^3}{\rho c_p} \tag{3-79}$$

where T is air temperature (K), and σ' is defined as:

$$\sigma' = \sigma_f\ \xi_f\ (1 + \frac{\xi_g}{\xi_f + \xi_g - \xi_f\ \xi_g})\ \sigma \tag{3-80}$$

where σ_f is the canopy coverage coefficient, ξ_f and ξ_g are thermal emissivities of the canopy and bare soil, respectively, and σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

Evaporation from Soil or Water Surfaces

Evaporation from open water surfaces in wetlands

Based on field measurements (see CHAPTER 4), it was assumed in the model, that the hourly evaporation rate from the water surface of cypress wetlands was about 30 percent of the equilibrium evaporation rate:

$$E_s = 0.3\ E_{eq}\ \frac{A(h)}{A} \tag{3-81}$$

where E_{eq} is the equilibrium evaporation (mm hr^{-1}), A(h) is the wetland area covered by standing water (m^2), which is a function of water depth h (m), A is the delineated wetland area (m^2), and 0.3 is the coefficient determined by field measurements.

Evaporation from the soil surface in uplands

It is very difficult to estimate soil evaporation in forests. However, results based on a chamber method showed that daily soil evaporation rate was about 0.3 mm (Brown, 1978). Soil evaporation decreased exponentially with the decrease of water table (Brutsaert, 1982). When the water table in pine uplands dropped 0.7 m below ground, surface soil (0-10 cm) moisture reduced to its wilting point if no rainfall was added to the surface (see Chapter 4), which makes soil evaporation very low. It was assumed that the soil evaporation rate is the same as the evaporation from wetland water surfaces when the water table is at or above the ground surface:

$$E_s = 0.3\, E_{eq}\, e^{-4\, WT} \qquad (3\text{-}82)$$

where WT is the depth of water table from the soil surface (m). From this equation, it can be seen that when the water table is 0.7 m deep, soil evaporation drops to only about 6 percent of its potential evaporation rate.

CHAPTER 4
EXPERIMENTAL RESULTS AND DISCUSSION

Stand Structure and Radiation

Plant Inventory

Cypress wetlands

Pond cypress and slash pine were the dominant canopy species in all three wetlands (Figure 4-1 and Table 4-1). Cypress accounted for 53, 69 and 46 percent in the C, K and N wetlands, respectively, in terms of species importance value (Figure 4-1). Slash pine accounted for an average of one third of the total importance value in all wetlands. In the N wetland, black gum (*Nyssa sylvatica* var. *biflora*) was also quite frequent with an importance value of 16 percent. Other canopy species included *Persea palustris*, *Myrica cerifera*, *Ilex cassine*, and *Acer rubrum*, but their total importance value did not exceed 5 percent. Ferns, sedge and other shrubs are the main understory species.

The mean height of trees was 14.4, 14.2 and 9.1 m for cypress, pine and hardwoods, respectively, in these three wetlands (Table 4-2). The corresponding DBH was 16.6, 12.7 and 9.4 cm for cypress, pine and hardwoods. Cypress trees in the wetland K were larger than those in other wetlands, but the density was lower. The average tree density in these three wetlands was 2009 ± 718 stems ha^{-1}.

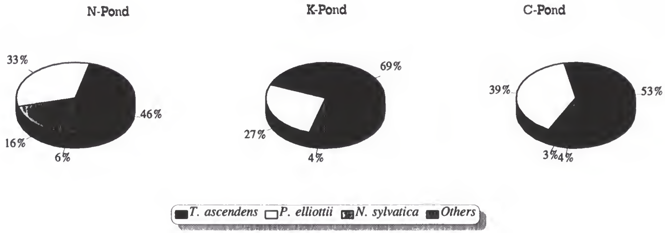


Figure 4-1. Relative importance of tree species in cypress wetlands.

Table 4-1. Species composition and their importance in cypress wetlands

Wetland	Species	Tree Density (#/ha)	Basal Area (m^2/ha)	Rel. Freq. (%)	Basal Area (%)	Importance Value (%)
C	*Taxodium ascendens*	1000	24.81	49	58	53
	Pinus elliottii	831	16.51	40	38	39
	Nyssa sylvatica	85	0.86	4	2	3
	Persea palustris	77	0.16	4	0	2
	Myrica cerifera	38	0.23	2	1	2
	Ilex cassine	23	0.30	1	1	1
	Acer rubrum	8	0.07	0	0	0
	Total	2062	42.94	100	100	100
K	*Taxodium ascendens*	783	26.55	62	76	69
	Pinus elliottii	383	8.11	30	23	27
	Acer rubrum	42	0.13	4	1	2
	Persea palustris	33	0.04	3	0	1
	Ilex cassine	17	0.05	1	0	1
	Vaccinium spp.	8	0.01	0	0	0
	Total	1266	34.89	100	100	100
N	*Taxodium ascendens*	1100	21.43	41	52	46
	Pinus elliottii	788	14.94	29	36	33
	Nyssa sylvatica	562	4.31	21	10	16
	Persea palustris	162	0.38	6	1	3
	Ilex cassine	62	0.29	2	1	2
	Myrica cerifera	25	0.11	1	0	0
	Total	2699	41.46	100	100	100

The wetland species composition, DBH, height and stand density were similar to other cypress wetlands in the area (Table 4-2). However, the frequency of slash pine was much higher than reported in the literature. The densities of slash pine in the C and N wetlands were higher than the overall mean plus 1 standard error in Table 4-2.

Deeper wetlands had higher cypress importance values. The cypress importance values of the K, C and N wetlands, with a maximum depth of 0.42, 0.39 and 0.33 m, were 69, 53 and 46 percent, respectively (Table 4-1). Meanwhile, the importance values of broadleaved species in the K, C and N wetlands were 4, 8 and 21 percent, respectively, which were inversely related to wetland depth. The relationships between the depth of wetlands and importance values of cypress and hardwood species were consistent with the observation of Marois and Ewel (1983) for 15 cypress wetlands in Florida. Because of the high densities of slash pine in the C, K and N wetlands, their basal areas were also higher than in other wetlands (Tables 4-2 and 4-3). However, the total basal areas of the wetland stands were close to that of the regional average.

Pine uplands

Slash pine (*Pinus elliottii*) was the only tree species in the uplands. Tree densities of these plots were quite low because of the 5th row thinning performed six years ago (Table 4-4). However, total leaf area per tree appeared to be higher than that of the slash pine plantations at normal planting density in the region. Understory species included saw palmetto and gallberry.

Table 4-2. General characteristics of the study cypress wetlands C, K and N, and other similar cypress wetlands in Florida.

Study	Area	Height (m)			DBH (cm)			Density (Stem No./ha)				Source
Site	(ha)	Cyp[1]	HW[2]	Pine	Cyp[1]	HW[2]	Pine	Cyp[1]	HW[2]	Pine	Total	
C	0.70	13.4	10.2	14.7	16.2	10.8	14.1	1000	231	831	2062	This Study
K	0.74	15.6	6.1	11.3	19.2	6.4	14.1	783	100	383	1266	Ibid
N	0.54	14.2	10.9	16.6	14.4	11.1	10.0	1100	812	788	2700	Ibid
Morningside Park	1.00	15.3	4.4		15.4	6.3	14.1	1617	617	83	2317	Brown, 1978
Odum's	1.00	14.7	14.0	21.3	15.9	14.6	24.5	1783	317	50	2150	Ibid
Owens-Illinois	0.93	13.8	6.1	21.1	13.7	4.8	23.1	2567	1250	83	3900	Ibid
Austin Cary	4.50	20.2	7.5		25.5	7.0		888	3063		3951	Ibid
Hague	0.15	15.7	9.1	17.1	25.9	15.3	22.7	237	414	33	684	Ibid
Groundwater	0.69	17.5	8.6	9.6	21.6	10.4	10.6	667	139	12	818	Ibid
Burnt Dome (S-1)	0.51	17.1	10.1	14.2	24.0	17.7	17.9	484	6	13	503	Ibid
Sewage Dome 2	1.07	11.7	7.2	10.3	13.5	7.6	13.7	1567	926	80	2573	Ibid
Mean	1.08	15.4	8.6	15.1	18.7	10.2	16.5	1154	716	236	2084	
Std. Err.	0.35	0.7	0.8	1.3	1.4	1.3	1.6	203	262	97	359	

[1] Cypress, or *Taxodium ascendens*

[2] Hardwoods

Table 4-3. Leaf litterfall and LAI of the study cypress wetlands C, K and N, and other similar cypress wetlands in Florida.

Site	Basal Area (m^2 ha^{-1})				Leaf Litterfall (g m^{-2} yr^{-1})				LAI (m^2 m^{-2})				Source
	Cyp[1]	HW[2]	Pine	Total	Cyp[1]	HW[2]	Pine	Total	Cyp[1]	HW[2]	Pine	Total	
C	24.8	1.6	16.5	42.9	204.1	12.3	142.9	359.3	2.5	0.3	1.6	4.5	This Study
K	26.6	0.2	8.1	34.9	262.6	2.5	59.5	324.6	3.3	0.1	0.7	4.0	Ibid
N	21.4	5.2	14.9	41.5	126.2	102.9	98.1	327.2	1.6	2.8	1.1	5.5	Ibid
Morningside Park	44.3	5.0	1.7	51.0	332.2	25.2	57.6	415.0	4.1	0.7	0.6	5.5	Brown, 1978
Odum's	47.0	5.7	2.5	55.2	364.2	32.7	6.7	403.6	4.5	0.9	0.1	5.5	Ibid
Owens-Illinois	51.6	3.2	4.0	58.8	390.4	115.5	225.5	731.4	4.8	3.2	2.5	10.5	Ibid
Austin Cary	54.2	16.6	0.0	70.8	258.6	146.4	4.9	409.9	3.2	4.0	0.1	7.3	Ibid
Groundwater	32.7	1.4	0.1	34.2	305.5	8.8	0.0	314.3	3.8	0.2	0.0	4.0	Ibid
Burnt Dome (S-1)	24.0	0.1	0.4	24.5	163.2	0.0	0.0	163.2	2.0	0.0	0.0	2.0	Ibid
Sewage Dome 2	33.0	1.6	2.3	36.9	536.4	75.3	9.4	621.1	6.7	2.1	0.1	8.8	Ibid
Mean	36.0	4.1	5.1	45.1	294.3	52.2	60.5	407.0	3.7	1.4	0.7	5.8	
Std. Err.	3.9	1.5	1.9	4.4	38.0	16.9	23.9	51.1	0.5	0.5	0.3	0.8	

[1] Cypress, or *Taxodium ascendens*
[2] Hardwoods

Table 4-4. Tree and stand characteristics of slash pine uplands.

Plot	Stand Density (#/ha)	DBH (cm)	Height (m)	F.L.B.[a] Height (m)	Width of Crown (m)			
					N	E	S	W
C	672	16.8(4.6)	14.1(2.6)	9.3(1.3)	1.2(.5)	1.2(.5)	1.3(.6)	1.3(.5)
K	496	20.7(4.5)	16.3(2.6)	10.0(1.1)	1.5(.7)	1.5(.5)	1.7(.5)	1.4(.5)
N	464	17.6(3.9)	14.6(2.6)	9.4(1.9)	1.3(.5)	1.3(.5)	1.4(.5)	1.2(.5)

[a] First live branch

Dynamics of Litterfall and Leaf Area Index

Litterfall

The K and N wetlands produced almost the same amount of total leaf/needle fall from April 1993 to March 1994, while the C wetland produced 10 percent more than the K and N wetlands (Table 4-5). The composition of leaf/needle litterfall was quite different among wetlands, but the composition was well in line with the species composition of these plots (see Figure 4-1). Cypress leaf litterfall (LL) accounted for 57, 80 and 38 percent of the total leaf/needle litterfall, while slash pine needle litterfall (NL) accounted for 40, 18 and 30 percent of the total leaf/needle litterfall in the C, K and N wetlands, respectively. This indicated that the leaf/needle litterfall of cypress and slash pine combined accounted for more than 97 percent in the C and K wetlands. Leaf fall of black gum explained 31 percent of the total in the N wetland.

Table 4-5. Cumulative leaf/needle fall from April 1, 1993, to March 31, 1994.

	Wetland			Upland		
Species	C	K	N	C	K	N
T. ascendens	204.1	262.6	126.2	------	------	------
P. elliottii	142.9	59.5	98.1	167.2	210.0	164.4
N. sylvatica	12.3	2.5	102.9	------	------	------
Total	359.3	324.6	327.2	167.2	210.0	164.4

Leaf litterfall occurred mainly from October to December for the deciduous species of cypress and black gum (Figures 4-2 and 4-3). Needle fall of slash pine showed more of a bell-shaped pattern peaking from June to December (Figure 4-4). The large amount of needle litterfall in September 1993 was the direct effect of a hurricane, which subsequently caused a small reduction in October.

The cypress LL in the C, K and N wetlands was lower than the regional average (Table 4-3). In fact, cypress LL at the N wetland was the lowest of all the wetlands reported. Sewage dome 2 had the highest cypress LL, although its basal area was below the average. Extraordinary production of cypress LL was triggered by the application of sewage (Brown, 1978).

As expected, the pine NL in the C, K, and N wetlands was consistent with the respective basal areas of pine trees (Table 4-3). However, the highest pine NL appeared

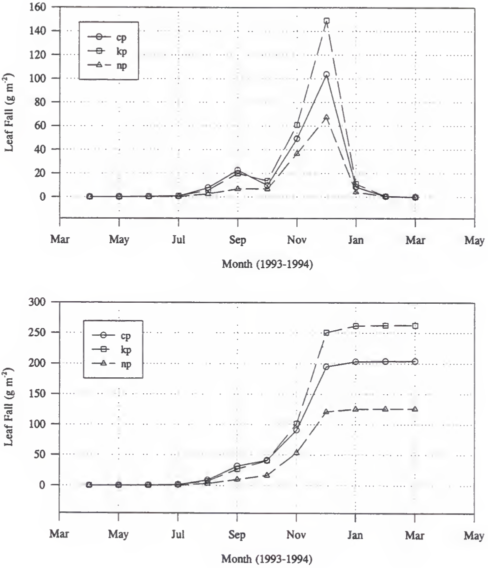
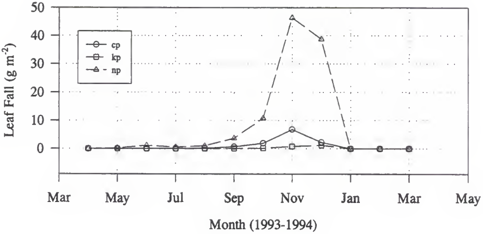


Figure 4-2. Monthly (upper panel) and cumulative (lower panel) leaf litterfall of cypress in wetlands.



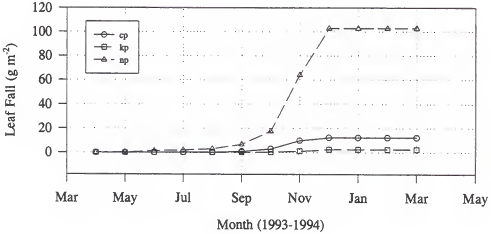
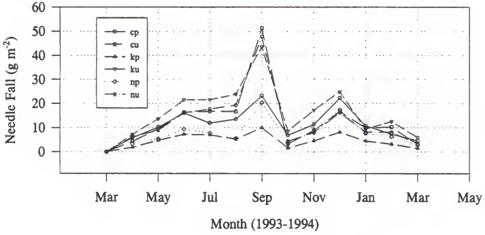


Figure 4-3. Monthly (upper panel) and cumulative (lower panel) leaf litterfall of black gum in wetlands.



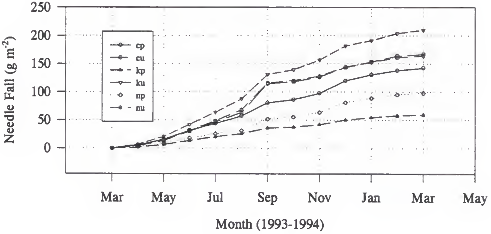


Figure 4-4. Monthly (upper panel) and cumulative (lower panel) pine needle litterfall in both uplands and wetlands.

at Owens-Illinois, which only had a basal area of 4.0 m^2 ha^{-1} for pine. At Morningside Park, the considerable amount of pine NL of 57.6 g m^{-2} yr^{-1} was also reported with a very small basal area of 1.7 m^2 ha^{-1}. The inconsistency of the pine NL with its tree basal area found in previous studies (Table 4-3) might be the result of the non-representative sampling of litterfall or of plant inventory. For example in Brown's study (1978), the wetlands were divided into center (with a radius of 30 m) and edge zones for the plant inventory. Each of these zones had the same number of 10x10 m^2 plots. The equal allocation of sampling plots in the center and edge zones had the potential to misrepresent the average situation of the wetland investigated if an arithmetic average was applied, because the species composition, DBH and heights of trees were different in these zones.

The average total leaf litterfall would have been 339.6 ± 26.0 g m^{-2} when excluding the extraordinary Owens-Illinois site and Sewage Dome 2 (high leaf production by sewage fertilization). This value would be very close to the total annual leaf/needle litterfall of the C, K and N wetlands.

Seasonal changes in Leaf Area Index

The measured specific leaf areas (SLA), or the all-sided leaf area divided by the dry weight, were 111.4±1.6, 124.2±1.3, and 253.2±2.5 cm^2 g^{-1} for slash pine, cypress and black gum, respectively. These values were comparable to published data (Colbert et al., 1990; Chason et al., 1991; Dalla-Tea and Jokela, 1991; Gholz et al., 1991; Brown, 1978).

The K upland had the highest LAI of all three uplands, while the C and N uplands had a very similar amount of LAI and seasonal pattern (Figure 4-5). The temporal

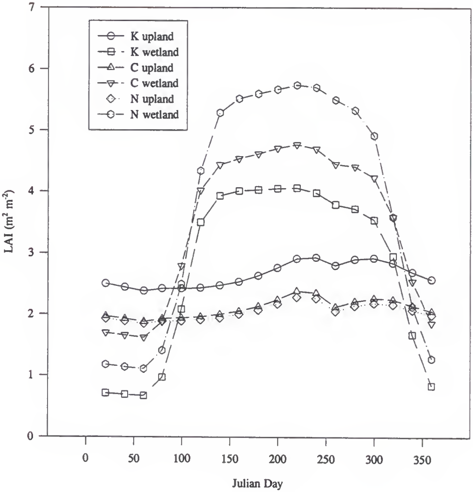


Figure 4-5 . Temporal change of leaf area index of cypress wetlands and slash pine uplands during 1993.

variation of LAI in the wetlands was higher than that in the uplands. Naturally, uplands had a higher LAI during the winter months, but the difference reversed during the summer months. The LAI in the cypress wetlands did not go to zero during the winter because of the presence of slash pine trees.

The seasonal change of LAI for each species was normalized (LAI_{norm}) by its annual total leaf litterfall (Figure 4-6 and Table 4-6). Cypress and black gum demonstrated a very similar normalized seasonal pattern, which may indicate that the seasonal change of LAI of deciduous tree species in this region could probably be predicted by one model. The LAI_{norm} of slash pine was always larger than one because of the two-year assumption for its needle-retention time. The all-sided LAI estimates for cypress and hardwoods were respectively 3.7 and 2.2 at Odum's, 2.5 and 4.7 at Austin Cary, 5.1 and 2.9 at Sewage Dome 2 as estimated from allometric growth relationships (Brown, 1978). By comparing these data with the data obtained from litterfall (Table 4-3), it can been seen that the values for hardwoods were overestimated and that of cypress underestimated. The average LAI would have been 5.2 ± 0.5 m^2 m^{-2}, if Owens-Illinois and Sewage Dome 2 have been excluded, which is not significantly different from the average of 5.8 ± 0.8 m^2 m^{-2} when all wetlands were included. These data indicated that the maximum overstory LAI of cypress wetlands in Florida was about 8 m^2 m^{-2}, which was higher than that of slash pine uplands with a maximum value of 6 m^2 m^{-2} (Gholz, 1986). The average LAI of wetlands was about 5.5 m^2 m^{-2}. Therefore, the LAI of the N wetland represented the average, but the LAI of the C and K wetlands was lower than the average. The proportion of pine LAI in the C and N wetlands was higher than the overall average.

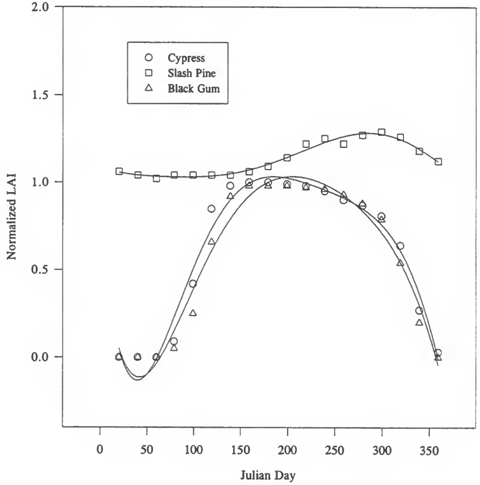


Figure 4-6. Normalized temporal change of leaf area index of slash pine, cypress and black gum in 1993. Leaf area index was normalized by total annual leaf/needle fall.

Table 4-6. Regression coefficients for normalized LAI* of slash pine, cypress and black gum.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	R^2
T. ascendens	0.1370	-1.7246	3.5618	-1.6066	-0.0151	0.1251	-0.0200	0.96
N. sylvatica	0.0921	-1.1384	1.9653	-0.2989	-0.3837	0.1577	-0.0177	0.96
P. elliottii	1.0937	-0.0984	-0.1550	0.2818	-0.1149	0.0172	-0.0001	0.95

* $LAI_{norm} = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5 + b_6 x^6$ where x is (Julianday)/100.

Understory Leaf Area Index

The frequency of gallberry was very low in the upland plots and was not considered any further. The estimated LAI of palmetto showed that the C upland had the highest LAI of 1.73 m^2m^{-2} on an all-sided basis (Table 4-7). Palmetto LAI was 0.73 and 0.89 m^2m^{-2} in the K and N uplands, respectively. The estimates based on the assumption by the author of an equitriangular palmetto leaf shape showed a good agreement with the results calculated by Gholz's empirical equations (personal communication).

Radiation Transfer and Vertical Distribution of Leaf Area Index

Radiation transfer

The PAR was more rapidly attenuated in pine than in cypress crowns (Figure 4-7). This was probably caused by the fact that pine needles were more clumped around the twigs and had a higher density in space. On the other hand, cypress leaves had a rather vertical angle distribution (Figure 4-8), which decreases radiation interception and therefore reduces the potential of becoming overheated and thus reduces the amount of water being evaporated from the leaves.

Table 4-7. Leaf area index of palmetto in pine uplands.

Upland	Leaf # per stem	mean Area per leaf (m^2)	Density (stems/ha)	LAI	LAI_T[§]
C	5.1	0.1569	21600	1.73	1.84
K	8	0.1191	9600	0.73	0.72
N	3.8	0.1373	17200	0.89	0.91

[§] LAI calculated by assuming that a palmetto leaf has an equitriangular shape.

The PAR attenuation pattern in the wetland canopies was similar to that in individual crowns (Figure 4-9). Only about 10 percent of the radiation penetrated the wetland canopies in the early morning, because the pathway for light to reach the ground was longer, increasing the chance for light to be intercepted by canopy elements. At noon, the percentage of light penetration was 40 percent. The PAR attenuation in the upland canopy was more difficult to measure because of the frequency and size of canopy gaps.

Light extinction coefficient. In most forest canopy models, the radiation attenuation in a forest canopy has been predicted by the Beer-Lambert equation (e.g., Shuttleworth, 1989; Cropper and Gholz, 1993; see Eq. 2-12). In this equation, the extinction coefficient is an important parameter which influences the accuracy of radiation prediction. The Beer-Lambert equation underestimated the LAI based on PAR measurements using an extinction

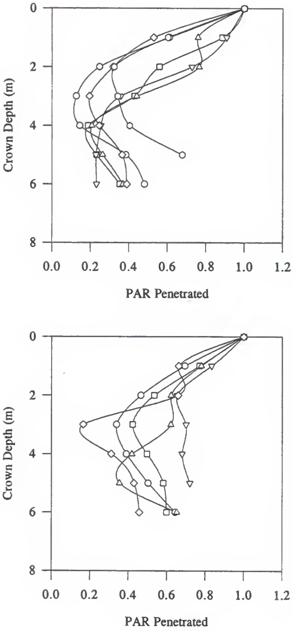


Figure 4-7. Vertical distribution of photosynthetically active radiation in the crowns of six individual slash pine (upper panel) and five cypress (lower panel) trees. Data were taken near solar noon during the summer of 1993.

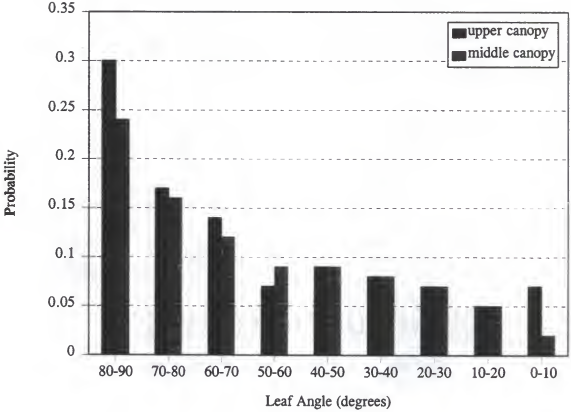


Figure 4-8. Leaf angle distribution of cypress leaves in wetlands.

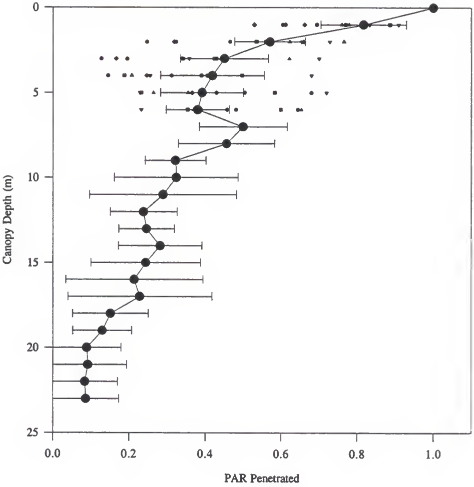


Figure 4-9. Penetration of photosynthetically active radiation in cypress canopies. Unconnected points are measurements in individual tree crowns.

coefficient of 0.5 (Figure 4-10). An optimized extinction coefficient of 0.35 was obtained based on PAR measurements and direct LAI estimates. The value 0.35 was equivalent to 0.175 on an all-sided or 0.55 on a projected LAI basis. It was within the range of the values reported for seven coniferous forests (0.47±0.11 projected LAI, Jarvis and Leverenz, 1983) and was similar to the June value of 0.17 (all-sided) of slash pine forests (Gholz et al., 1991; Cropper and Gholz, 1993).

Vertical distribution of Leaf Area Index

The LAI-2000 Canopy Analyzer is supposed to be used in closed canopies, because it is based on the assumption of a random distribution of canopy elements in space. The results showed that it can also be used to measure LAI in open forests (Figure 4-11). The relationship was consistent with the values reported for other forests, both broadleaved and coniferous (Chason et al., 1991; Sternberg et al., 1994). However, it was found that all the LAI-2000 measurements were only about one quarter of the direct LAI.

Both the LAI-2000 and the Ceptometer measurements showed a similar pattern for the vertical distribution of SAI in all wetlands (Figure 4-12). The vertical distribution data of SAI were fitted to a fourth order polynomial equation, of which the coefficients have been listed in Table 4-8.

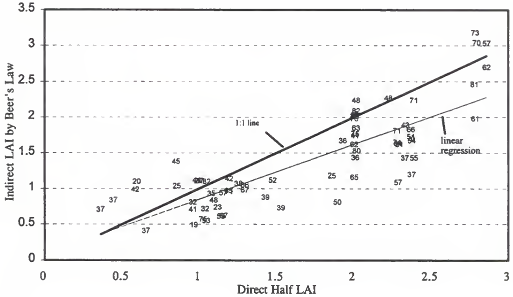


Figure 4-10. Comparison of direct and indirect estimates of leaf area index (LAI). Indirect LAI was calculated from Ceptometer measurements by using the Beer-Lambert law and an extinction coefficient of 0.5. Numbers in the graph represent the solar elevation angles when the measurements were being taken.

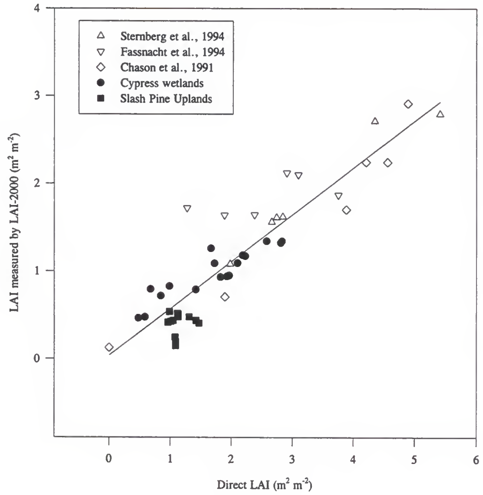


Figure 4-11. Comparison of LAI-2000 measurements with direct estimates of leaf area index in forest stands.

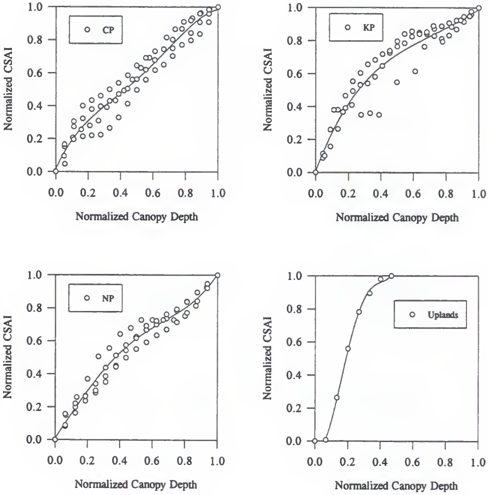


Figure 4-12. Vertical distribution of cumulative surface area index (CSAI) in cypress wetlands (indicated by P) and slash pine uplands.

Table 4-8. Regression coefficients of the polynomial equations describing the normalized vertical distribution of leaf area index in the canopies.

Plot	b_0	b_1	b_2	b_3	b_4	R^2
C Wetland	0.017	2.216	-4.452	6.207	-2.913	0.96
K wetland	0.004	2.707	-3.741	2.671	-0.652	0.93
N wetland	0.010	1.464	0.326	-2.580	1.787	0.97
Uplands	-0.003	-2.447	50.635	-149.456	133.098	0.99

Rainfall Interception

Storage Capacity

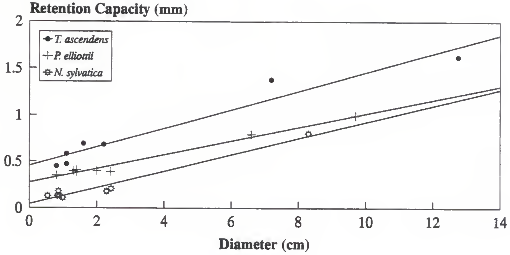
Storage capacity of leaves, branches and stems

The measured rainfall retention capacity of foliage of pine, cypress and black gum were 0.0384, 0.0367 and 0.0411 mm, respectively, expressed on a unit LAI basis. Because of the low values of these measurements and since there was no significant difference among them, the value of 0.04 was used for all species in this study.

Branch and stem retention capacity increased with increasing diameter for all tree species (Figure 4-13). This could be explained by the change of bark thickness and associated fracturing. The larger the diameter, the thicker the bark, and therefore the higher the retention capacity. In addition, retention capacity of branches and stems was also dependent on the characteristics of the bark, such as texture and surface roughness. Cypress bark was softer and less water-repellent compared with the other two species, and therefore its retention capacity was the highest.

Scaling up storage capacity to canopy level

The surface area index of stems (BAI_s) ranged from 0.25 to 0.47 $m^2\ m^{-2}$ for cypress wetlands and 0.13 to 0.19 $m^2\ m^{-2}$ for pine uplands (Table 4-9). The variation was determined by the variation in stem density, basal area and canopy height. The total bark surface area index (BAI) was obtained from the intercept of the linear regression of total surface area index (SAI), estimated by light attenuation information, and direct LAI estimates. The branch area index (BAI_b) was the difference between this BAI and BAI_s.



T. ascendens: y=0.455+0.100D R=0.97
P. elliottii: y=0.278+0.074D R=0.99
N. sylvatica: y=0.044+0.088D R=0.98

Figure 4-13. Surface retention capacity of branches and stems as a function of diameter and tree species.

Table 4-9. Estimated storage capacities (C) of the foliage, branches and stems in the canopies.

Plot	Species	Basal Area (m^2 ha^{-1})	Tree # (# ha^{-1})	Height (m)	DBH (cm)	LAI	BAI	BAI_s	BAI_b	C_{stem} (mm)	C_{branch} (mm)	$C_{foliage}$ (mm)	C_m (mm)
CP	*T. ascendens*	24.81	1000	13.4	16.2	2.42		0.21	0.21	0.27	0.16	0.10	0.52
	P. elliottii	16.51	831	14.7	14.1	2.05		0.17	0.17	0.14	0.09	0.08	0.30
	Hardwoods	1.54	231	10.2	10.8	0.33		0.02	0.02	0.01	0.01	0.01	0.03
	Total					4.80	0.8	0.40	0.40	0.41	0.25	0.19	0.85
KP	*T. ascendens*	26.6	783	15.6	19.2	3.17		0.23	0.49	0.32	0.37	0.13	0.81
	P. elliottii	0.2	383	11.3	14.1	0.83		0.01	0.02	0.01	0.01	0.03	0.05
	Hardwoods	8.1	100	6.1	6.4	0.07		0.02	0.04	0.01	0.01	0.00	0.02
	Total					4.07	0.8	0.25	0.55	0.33	0.39	0.16	0.89
NP	*T. ascendens*	21.4	1100	14.2	14.4	1.52		0.22	0.34	0.26	0.26	0.06	0.57
	P. elliottii	14.9	788	16.6	10	1.49		0.18	0.28	0.12	0.14	0.06	0.32
	Hardwoods	5.2	812	10.9	11.1	2.76		0.07	0.11	0.04	0.03	0.11	0.18
	Total					5.77	1.2	0.47	0.73	0.41	0.43	0.23	1.07
CU	*P. elliottii*	14.9	672	14.1	16.8	4.17	0.4	0.14	0.26	0.13	0.13	0.17	0.42
KU	*P. elliottii*	16.7	496	20.7	20.7	3.70	0.5	0.19	0.31	0.20	0.16	0.15	0.50
NU	*P. elliottii*	11.3	464	17.6	17.6	3.22	0.4	0.13	0.27	0.12	0.14	0.13	0.38
Gholz[1]	*P. elliottii*	25.9	1190	15.4	15.4	5.00	0.76	0.27	0.49	0.23	0.25	0.20	0.67

[1] Personal communication.

In the partition of BAI_b to different species, it was assumed that :

$$\frac{Species \quad BAI_b}{Canopy \quad BAI_b} = \frac{Species \quad BAI_s}{Canopy \quad BAI_s} \tag{4-1}$$

The ratios of BAI_b to BAI_s found in this study (Table 4-9) were within the range of the temperate tree species (Whittaker and Woodwell, 1967), but lower than tropical trees or individual trees growing in open spaces (Whittaker and Woodwell, 1967; Herwitz, 1985).

For the estimation of the storage capacity of branches and stems, the average diameter of the stems and branches needs to be known (see Figure 4-13). It was assumed that the average diameter of the stems was half the DBH, and a constant 3 cm diameter was assumed for branches.

Stems and branches had almost equal amounts of storage capacity at the canopy level (Table 4-9). The storage capacity of foliage (including both overstory and understory) was smaller and accounted only for about 18 to 40 percent of total storage capacity. More storage was accounted for by foliage in the uplands because of the higher ratio of LAI to BAI and the relatively lower bark storage capacity on an unit BAI basis of slash pine as compared to cypress.

The storage capacity of wetlands (average 0.94 mm) was about twice that of uplands (average 0.43 mm). The storage capacity of a slash pine plantation scaled up by the above-mentioned method was 0.67 mm (Gholz in Table 4-9), which agreed well with the estimate of 0.72 by the Leyton method (H. Gholz, personal communication). The average ratio of BAI_b to BAI_s of 1.83 obtained by the present study was used for the estimation of BAI_b for this site.

Rainfall Canopy Interception

There were some differences in rainfall measured between the wetland sites, but they were not significant (Table 4-10). The average annual rainfall from April 1993 to March 1994 was 1092 mm, which was lower than the long term mean of 1330 mm. The observed rainfall interception was 218, 289 and 266 mm, or 20, 26 and 24 percent of rainfall in the C, K and N wetlands, respectively. The K wetland had the highest interception.

Upland canopy interception was 159, 222 and 194 mm at the C, K and N plots, respectively, which was lower than that in the adjacent wetlands (Table 4-10). The difference in total interception at the ecosystem level between cypress wetlands and slash pine uplands will be appraised using modeling techniques because of the difficulty of

Table 4-10. Measured rainfall and interception, in mm, from April 1993 to March 1994.

Site	Rainfall (mm)	Upland		Wetland	
		Interception (mm)	Rainfall Percentage	Interception (mm)	Rainfall Percentage
C	1059	159	15	218	21
K	1109	222	20	290	26
N	1109	194	18	267	24
Mean	1092	192	18	258	24

measuring saw palmetto interception. In the slash pine uplands, palmetto "stemflow" was significant due to the funneling effect of its upright leaves.

Rainfall depth is one of the most frequently used and convenient independent variables to establish empirical regression equations with interception (Figure 4-14). Canopy interception increased with the increase of rainfall at all sites. More than 57 percent of the variation in monthly interception could be explained by rainfall alone (Table 4-11). The interception in the wetlands was better correlated with rainfall amount than in the uplands. The intercept in the linear regression between interception and rainfall in wetlands was higher than that in the uplands. This could be interpreted as an indication of the difference in storage capacity between the two ecosystems. The slope could be interpreted as the average evaporation per unit amount of rainfall. The wetlands evaporated about 5 mm more than the uplands per 100 mm rainfall.

The inclusion of air temperature (as an index of available energy) increased the proportion of variation in interception that could be explained by an empirical equation (Table 4-11):

$$I = a_0 + a_1 R + a_2 T + a_3 R T \qquad (4\text{-}2)$$

where I is monthly interception (mm), R is the amount of rainfall (mm), T is monthly air temperature (°C), and a_0, a_1, a_2 and a_3 are regression coefficients. Although these equations are useful in revealing some characteristics of interception in the two ecosystems, they are empirical and therefore site-specific.

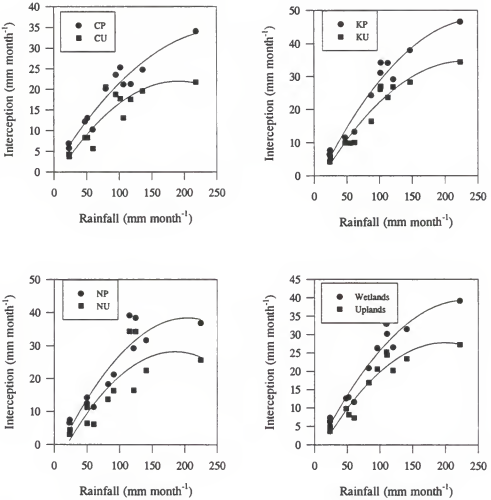


Figure 4-14. Relationship between monthly interception and rainfall measured in cypress wetlands (P) and slash pine uplands (U) from April 1 of 1993 to March 31 of 1994. C, K and N are sites.

Table 4-11. Coefficients in the empirical regression equations of interception and rainfall and temperature. See text for equation description.

Plot	Independent Variables	a_0	a_1	a_2	a_3	r^2
CP	Rainfall	5.22	0.1467			0.88
KP		4.10	0.2095			0.89
NP		5.15	0.1849			0.75
CU		4.25	0.1019			0.67
KU		2.95	0.1684			0.86
NU		2.90	0.1440			0.57
Wetlands		4.80	0.1836			0.87
Uplands		3.53	0.1369			0.78
CP	Rainfall, Temperature	-3.54	0.1507	0.4190		0.97
KP		0.28	0.1400		0.0059365	0.98
NP		12.36		-0.6708	0.0126771	0.95
CU		1.93	0.0425		0.0043245	0.83
KU		0.20	0.0987		0.0049989	0.96
NU		-0.91			0.0092834	0.84
Wetlands		5.33	0.1039		0.0056780	0.98
Uplands		20.92		-1.2117	0.0094690	0.98

Rainfall interception demonstrated an apparent seasonal pattern in both the uplands and wetlands (Figures 4-15 and 4-16). Although interception generally increased with rainfall depth as demonstrated above and in Figure 4-15, the interception ratio, or interception divided by rainfall, did not necessarily follow this pattern (Figure 4-16). For example, rainfall in January of 1994 was the highest, but the interception ratio was the lowest, suggesting that evaporation during rainfall may have been an important part of interception in the two ecosystems. The interception ratios generally peaked during July and September, when the evaporation potential and LAI were the highest, and were the lowest during the winter months.

Discussion

Storage capacity

The overall average leaf/needle water storage capacity reported for eight tree species was 0.068 mm per unit LAI and varied between 0.032 mm for *Eucalyptus maculata* to 0.178 mm for *E. pauciflora* (Aston, 1979). The averaged leaf storage capacity of five tree species in a tropical forest varied from 0.112 to 0.161 mm in still air and 0.031 to 0.058 in windy conditions (Herwitz, 1985). However, the values obtained by Monson and colleagues (1992) were at least an order of magnitude lower in most cases. For the same species of *E. mannifera*, Aston's estimate was 0.067 mm, which was double the estimate of 0.028 mm made by Crockford and Richardson (1990). The leaf storage capacity of cypress, slash pine and black gum of the present study varied around 0.04 mm, which was within the range of variation found for all tree species reported.

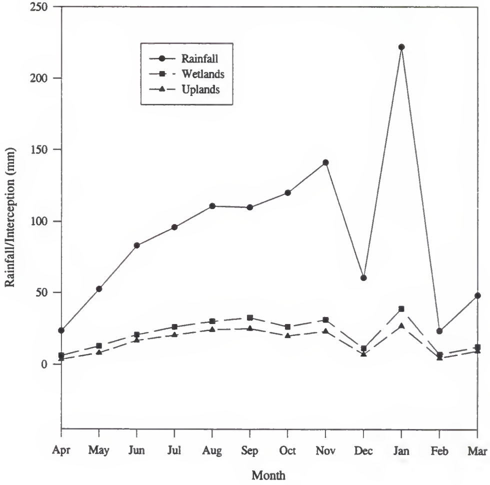


Figure 4-15. Seasonal changes of rainfall and interception in cypress wetlands and slash pine uplands measured from April 1 of 1993 to March 31 of 1994.

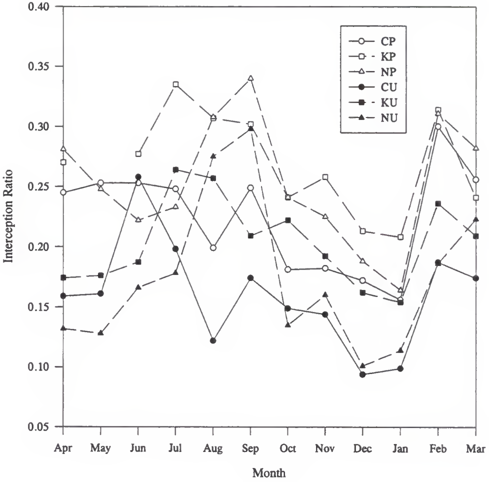


Figure 4-16. Seasonal changes of the interception ratio in cypress wetlands (P) and slash pine uplands (U) measured from April 1 of 1993 to March 31 of 1994. C, K and N represents sites.

It was demonstrated that the storage capacity of branch and stem surfaces of all three tree species *T. ascendens, N. sylvatica* and *P. elliottii* increased with increasing diameter. Similar results were reported for *Euclyptus macrorhyncha* (r=0.95), E. *rossii* (r=0.38) and *E. mannifera* (r=0.34) (Crockford and Richardson, 1990). The stem storage capacity of these species was 0.92, 0.13 and 0.07 mm, respectively. The stem storage capacity of cypress, slash pine and black gum of the present study would be 1.46, 1.02 and 0.92 mm, respectively, if the diameters were assumed to be 10 cm . The average branch and stem storage capacity of five tree species in a tropical forest varied from 0.120 to 0.718 mm (Herwitz, 1985). The values obtained by Herwitz (1985) were probably over-estimated because both the outside and inside of the bark were used to retain water in the laboratory, which would not happen in the field. The stem storage capacity of a flaky bark such as cypress was higher than that of a smooth bark (e.g., black gum). Similar results were obtained for tropical tree species (Herwitz, 1985).

The estimated storage capacity values of all cypress wetlands and slash pine uplands of the present study were comparable to the storage capacities of other forests (Table 4-12). Storage capacities of the 27 forests reviewed varied from 0.1 mm (Teklehaimanot et al., 1991), which represented a very open forest with a density of 156 stems ha^{-1}, to 1.5 mm (Massman, 1983), which represented a closed forest with a high LAI of 19 m^2 m^{-2}. The overall average storage capacity was 0.69±0.36 mm.

Rainfall interception

The average rainfall interception was 258 mm or 24 percent of the rainfall in the cypress wetlands, which was very close to the observation of 260 mm or 25 percent of

Table 4-12. Comparison of Canopy Rainfall Storage Capacities of Forests

Species	Density (# ha^{-1})	b_0	LAI	C_m	Method[1]	Country	Source and Note
Pinus Radiata	754	0.24	15.5	0.66			Whitehead and Kelliher, 1991
P. nigra	600	0.25		1.05	1	England	Rutter et al., 1971
P. sylvestris		0.26		0.8	1	England	Gash and Morton, 1978
P. pinaster	430	0.43	2.3	0.26	1	France	Lankreijer et al., 1992
P. sylvestris		0.13		1.02		England	Gash et al., 1980
P. elliottii	672	0.32	4.17	0.42	2	USA	This Study (summer; understory included)
	496	0.36	3.70	0.50	2	USA	Ibid
	464	0.4	3.22	0.38	2	USA	Ibid
Picea sitchensis	156			0.1	2'	Scotland	Teklehaimanot et al., 1991a, 1991b
	277			0.2	2'	Scotland	Ibid
	625			0.3	2'	Scotland	Ibid
	3000			1.09	2'	Scotland	Ibid

---

[1] 1=Leyton method; 2=Scaling up from stems, branches and leaves; 2'=Scaling up from trees ; 3=Optimization.

Table 4-12. ----- continued

Species	Density (# ha^{-1})	b_0	LAI	C_m	Method[1]	Country	Source and Note
T. ascendens	2062	0.24	4.80	0.85	2	USA	This study (summer; mixed species)
	1266	0.29	4.07	0.89	2	USA	Ibid
	2699	0.17	5.77	1.07	2	USA	Ibid
Pseudotsuga menziesii		0.09		1.2			Rutter et al., 1975 (S_s=0.9)
P. menziesii		0.05	19.2	1.5	1	USA	Massman, 1983
Quecus robur		0.45		0.88			Thompson, 1972 (summer)
		0.8		0.28			Thompson, 1972 (winter)
		0.3		0.8			Dolman, 1987 (summer)
		0.8		0.3			Dolman, 1987 (winter)
Q. rubra	600	0.31	4.9	0.7	1	Netherlands	Lankreijer et al., 1992 (Year: 1988)
	600	0.31	4.9	0.5	1	Netherlands	Ibid (year: 1989)
Eucalyptus	1525			0.39	2		
Mixed	3000	0.08		0.74	1'	Brazil	Lloyd, 1988
		0.03		0.61	1	Ivory Coast	Hutjes et al., 1990
		0.02		1.1	3	Java	Calder et al., 1986

[1] 1=Leyton method; 2=Scaling up from stems, branches and leaves; 2'=Scaling up from trees ; 3=Optimization.

rainfall made by Heimburg (1984). This was higher than the interception of the overstory of slash pine plantations (Table 4-13). The average interception was 24 and 17 percent of rainfall for cypress wetlands and slash pine uplands (understory of uplands not included), respectively. These values were within the range reported for forests around the world (Zinke, 1967; Blake, 1975; Table 4-13).

Evaporation From the Surface of Standing Water in Cypress Wetlands

In order to estimate evaporation from the wetland water surface, the evaporation rate (measured by a Class A pan) and the change of wetland area covered by standing water must be known. The latter can be monitored by recording water level changes over time if the relationship between water level in a wetland and its corresponding water surface area is available.

Relationship Between Water Level and Water Surface Area in Wetlands

The K wetland was the deepest and largest in extent among the three wetlands (Table 4-14). The elevations of the deepest points were 29.61, 29.47 and 28.12 m above mean sea level and the depth of the delineated wetlands was 0.39, 0.42 and 0.33 m in the C, K and N wetlands, respectively. The wetland depth was estimated as the elevation difference between the deepest point and the palmetto delineation line along the boundary of the wetland. Water levels in all the wetlands from Julian day 75 to 270 in 1992 (wet period) were close to the observed maximum. The average water levels during this period

Table 4-13. Comparison of annual interception loss of cypress wetlands with other forest ecosystems.

System	Location	Rainfall (mm)	Interception (mm)	Interception Percent	Source and Note
Cypress Wetlands	Florida, USA	1040	260	25	Heimberg, 1984
		1059	218	20	This study
		1109	290	26	Ibid
		1108	267	24	Ibid
Slash Pine Plantation	Florida, USA	1059	159	15	This study. Overstory only.
		1109	222	20	Ibid
		1108	194	18	Ibid
		1121	188	17	Gholz, personal communication.
		1200	152	13	Ibid
		1230	233	19	Ibid
Rain Forest	West Java	2851	600	21	Calder et al., 1986
Scots pine	East Anglia	896	245	27	Gash, 1980
Tai Forest	Ivory Coast	1022	94	9	Hutjes et al., 1990
P. nigra	England	1250	415	33	Rutter et al., 1971
P. radiata	New Zealand			33	Wells and Blake, 1972

were 0.39, 0.40 and 0.33 m in the C, K and N wetlands, respectively, which were close to the estimates using the palmetto delineation line.

All three wetlands demonstrated a similar nonlinear relationship between the surface area of the standing water and the corresponding water level (Figure 4-17). This relationship was well described by the following polynomial equation:

$$A(h) = a_1 h + a_2 h^2 + a_3 h^3 \qquad (4\text{-}3)$$

where A(h) (m^2) was the water surface area in the wetland as a function of the water depth h (m), and a_1, a_2 and a_3 were regression coefficients (Table 4-14). Based on these equations, the estimated wetland area was 7028, 7458 and 5357 m^2 in the C, K and N

Table 4-14. Wetland depth, wetland area, and coefficients a_1, a_2 and a_3 of the polynomial regression equation (see text for detail) describing the relationship between the surface area of the standing water and the water level in wetlands.

Wetland	H(m)	Area (m^2)	a_1	a_2	a_3	r^2
C	0.39	7028	2676.46	22717.59	42623.75	1.00
K	0.42	7458	1882.04	26193.13	27632.14	1.00
N	0.33	5357	-2708.85	22711.44	105131.5	1.00
Total	0.38	6350	-3101.60	60149.81	-21080.2	0.98

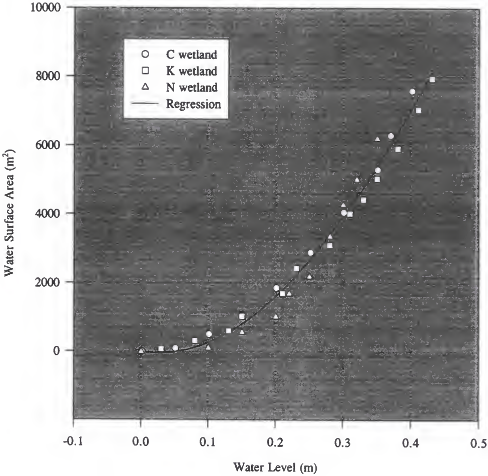


Figure 4-17. Surface area of standing water as a function of water level in cypress wetlands.

wetlands, respectively. The sizes of the three wetlands used in this study were smaller compared to the regional average, but all of them were within the band of one standard error (Table 4-2) .

Water Surface Evaporation in Wetlands

Data collected from April 1993 to April 1994 showed that monthly evaporation from the standing water in all three wetlands was about 30 percent of the open-pan evaporation measured at the Agronomy Weather Station, University of Florida, Gainesville, Florida, USA (Figure 4-18).

Evaporation From Standing Water in Wetlands

The level of standing water in all three wetlands changed significantly during the study period, and therefore the wetland area covered by standing water (Figures 4-19, 4-20 and 4-21). The potential evaporation rate of standing water, calculated as 30 percent of equilibrium evaporation rate, demonstrated a strong seasonal pattern. The actual evaporation from the water surface in wetlands was the potential evaporation weighted by the fraction of wetland area covered by standing water. It demonstrated a seasonal pattern similar to that of potential *evaporation* during a wet year (water level is higher than the palmetto line for more than half of the year) as during 1992, while it demonstrated a pattern similar to the changes of the wetland *area* covered by standing water during a dry year (water level is below ground surface for more than half of the year) as during 1993.

Water surface evaporation varied considerably from wetland to wetland (Table 4-15). For example, evaporation from the K wetland, which was the deepest in this study, could be two to several times higher than that from either the N or C wetland during

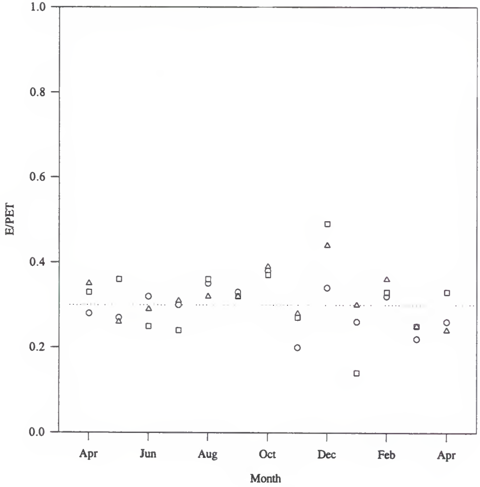


Figure 4-18. Temporal change of the ratio of pan evaporation in cypress wetlands to open pan evaporation at a standard weather station from 1993 to 1994.

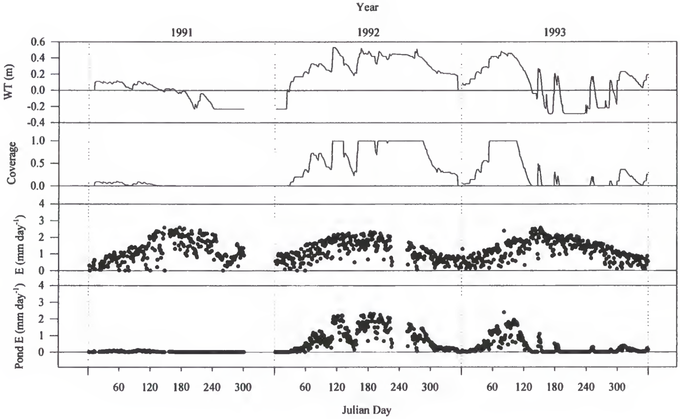


Figure 4-19. Daily variation of the depth and area coverage of the standing water, potential and actual evaporation from the water surface in the C wetland during 1991, 1992 and 1993.

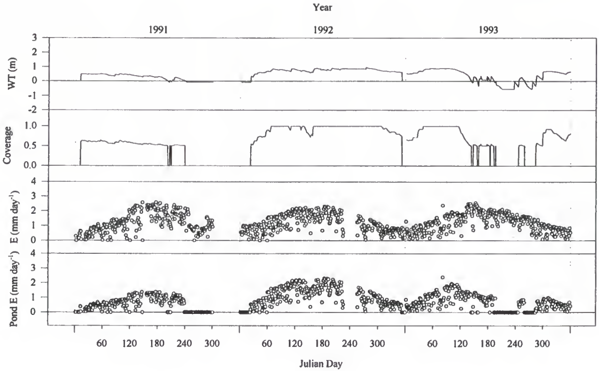


Figure 4-20. Daily variation of the depth and area coverage of the standing water, potential and actual evaporation from the water surface in the K wetland during 1991, 1992 and 1993.

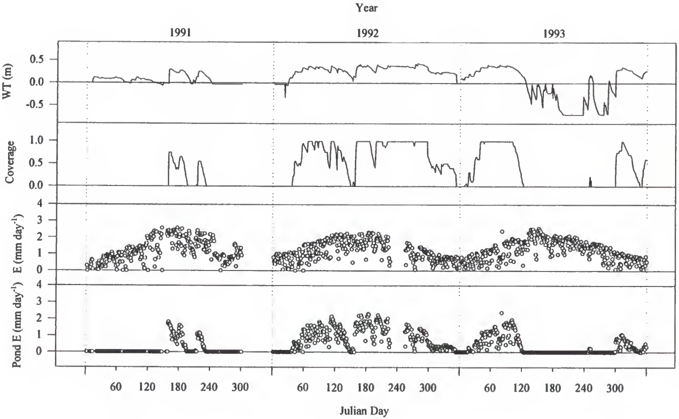


Figure 4-21. Daily variation of the depth and area coverage of the standing water, potential and actual evaporation from the water surface in the N wetland during 1991, 1992 and 1993.

Table 4-15. Estimated annual evaporation (mm) from the surface of standing water in wetlands.

Year	C Wetland	K Wetland	N Wetland	Mean	Std.Dev.
1991	6	159	55	73	45
1992	302	387	310	333	27
1993	110	228	118	152	38
Mean	139	258	161	186	37
Std.	87	67	77	77	

normal or dry years (e.g., 1991 and 1993). They were more similar during wet years (e.g., 1992). The temporal variation of water surface evaporation was even higher than its spatial variation. The spatial standard error was 37 mm, while the temporal error was 77 mm. The T-test showed that evaporation during a wet year (1992) was significantly higher than that of a dry year (1991), or a normal year (1993). The highest evaporation occurred during 1992 in the K wetland with an annual loss of 387 mm. It accounted for about 1/3 of annual rainfall in this region.

Daily Pattern of Transpiration and Stomatal Conductance at the Leaf/Needle Level

Figure 4-22 shows the daily pattern of PAR, air temperature, VPD, transpiration and g_s measured on May 17, 1993. Large spatial variation of PAR was encountered

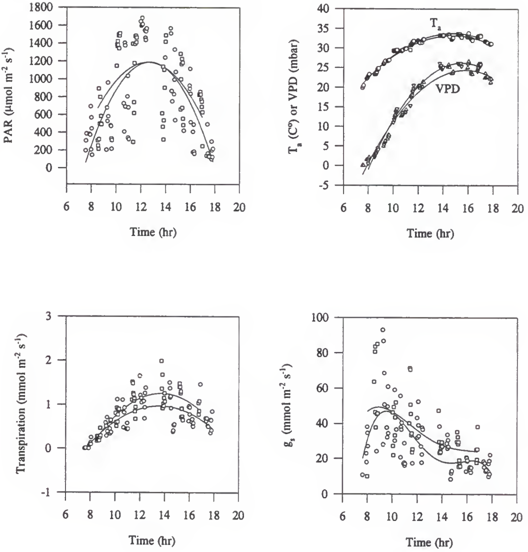


Figure 4-22. Daily patterns of photosynthetically active radiation, temperature, vapor pressure deficit, stomatal conductance and transpiration measured at various heights in trees in the canopies of K wetland (cypress: circles) and K upland (slash pine: squares) on May 17, 1993. Trends are shown by lines.

because the measurements were taken at different heights in trees in the canopy, while the spatial variability of VPD and air temperature was small. There were no significant differences with regard to these environmental variables between the wetland and upland. Large spatial variation of transpiration and g_s was found in both canopies. This was probably caused by the variability of PAR encountered in the canopies, and also by the spatial variation of transpiration and g_s among different trees.

Maximum transpiration and g_s occurred at noon and in the early morning, respectively (Figure 4-22). This reflected a multiple-variable control mechanism on both transpiration and g_s. In the early morning, stomatal conductance (g_s) increased with the increase of PAR. After nine o'clock, the effect of VPD became stronger than that of PAR, which led to the decrease of g_s. This type of daily pattern of transpiration and g_s was similar for other species (Jarvis et al., 1976; Lindroth, 1985). There was no significant difference between the two species studied with respect to the daily patterns of transpiration and g_s.

Relationship Among Stomatal Conductance and Environmental Variables

Plots of g_s against PAR, VPD and T (Figures 4-23, 4-24, 4-25 and 4-26) showed that our measurements covered a wide range of environmental conditions. Stomatal conductance (g_s) increased more rapidly with the increase of PAR in the early morning when VPD was small (Figures 4-23 and 4-24). However, this relationship was modified by the co-effect from other variables (e.g., VPD and air temperature, Figures 4-25 and 4-

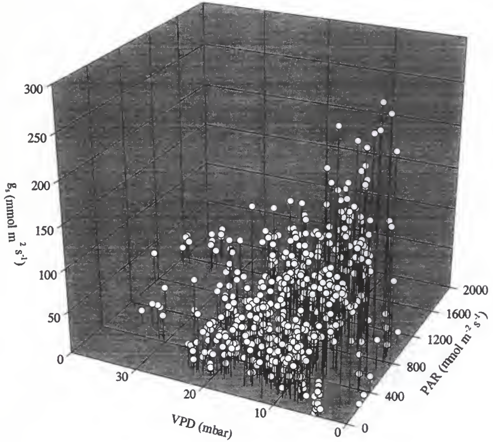


Figure 4-23. Relationship among stomatal conductance of cypress and photosynthetically active radiation and vapor pressure deficit of the air.

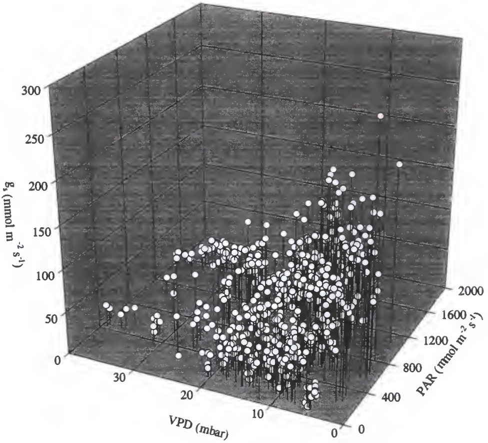


Figure 4-24. Relationship among stomatal conductance of **slash pine** and photosynthetically active radiation and vapor pressure deficit of the air.

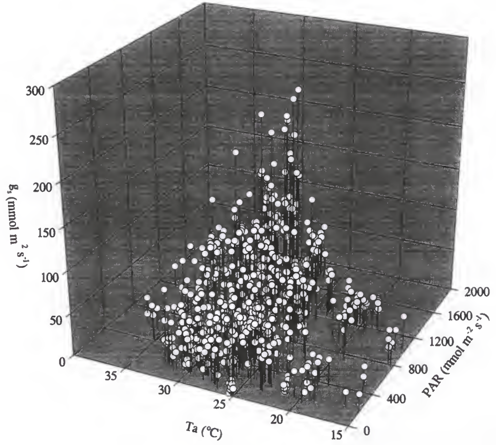


Figure 4-25. Relationship among stomatal conductance of cypress and photosynthetically active radiation and air temperature.

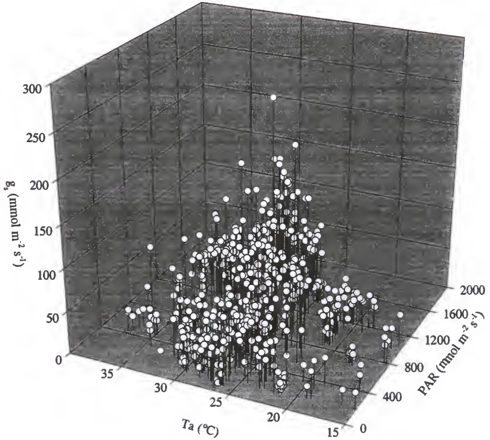


Figure 4-26. Relationship among stomatal conductance of **slash pine** and photosynthetically active radiation and air temperature.

26). In other words, at the same PAR level, stomatal conductance (g_s) changed with the change of other variables, such as VPD and air temperature. Stomatal conductance (g_s) increased with air temperatures below 30 °C, but it decreased thereafter. This may indicate that 30 °C is the optimal temperature for stomatal functioning for both species. Stomatal conductance (g_s) decreased exponentially with the increase of VPD. In all, there was no close relationship between g_s and any of these single variables.

Comparison of Transpiration and Stomatal Conductance between Species at the Leaf/Needle Level

According to the measurements taken during the growing season of 1993, there was no significant difference between the seasonal average g_s of slash pine of 71 mmol m^2 s^{-1} and cypress of 72 mmol m^2 s^{-1}, (Table 4-16). The average seasonal transpiration of slash pine was 0.52 mmol m^2 s^{-1}, which was lower than that of cypress of 0.55 mmol m^2 s^{-1}. However, the difference was not significant.

Estimation of ET from Water Level Fluctuations

In Cypress Wetlands

Maximum daily ET of the Bradford Forest wetland was about 8 mm in both 1987 and 1988 (Figure 4-27). This is consistent with the ETM prediction in this study as discussed later (see CHAPTER 5) by considering that the maximum transpiration rate was about 5 mm day^{-1} and the maximum evaporation rate from the water surface was about 3

Table 4-16. Comparison of transpiration and g_s between pond cypress and slash pine

Species	Tr (mmol m^2 s^{-1})	g_s (mmol m2 s-1)	PAR (μmol m^2 s^{-1})	VPD (mbar)	T_a (C°)	n
P. elliottii	0.52 ±0.01	71 ±3	925 ±19	15 ±0	28 ±0	665
T. ascendens	0.55 ±0.01	72 ±3	804 ±20	15 ±0	28 ±0	632
Difference	-0.03	-1	121[†]	0	0	

[†] Significant at $\alpha = 0.05$.

mm day^{-1}. Evapotranspiration was not estimated during some periods such as June to July in 1987 and June to August in 1988 because the water level dropped below the wetland bottom. There was no standing water in the wetland during these periods. In order to estimate annual ET, the monthly averages of daily ET of June, July and August were assumed to be equal to the maximum of that year, and ET of February was estimated as the mean of ET of January and March. Monthly averages of daily ET were obtained from the daily ET estimates (90 records in 1987 and 95 in 1988) (Figure 4-28). The values were consistent with the predicted transpiration by ETM as discussed later (see Chapter 5). The estimated annual ET was 995 and 941 mm in 1987 and 1988, respectively.

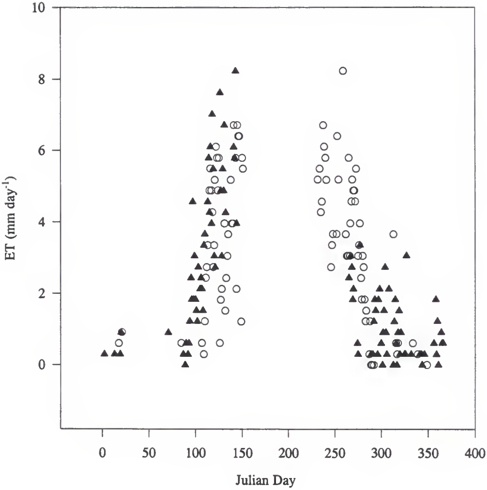


Figure 4-27. Daily variation of the evapotranspiration estimated from the water level fluctuations in the Bradford forested wetland during 1987 (triangles) and 1988 (circles).

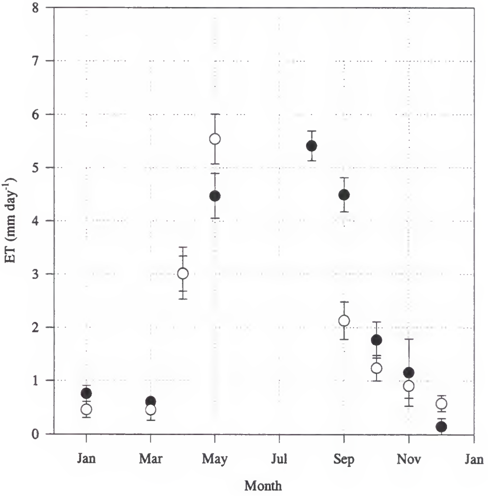


Figure 4-28. Monthly averages of the daily evapotranspiration estimated from water level fluctuation in the Bradford forest wetland during 1987 (empty circles) and 1988 (solid circles).

In the Uplands

The relationship of soil moisture measured by TDR and the depth of the water table has been shown in Figures 4-29 and 4-30. The relationship is affected by both spatial variability and the length of the time between the previous rainfall and when the measurements were taken. In addition, most of the porosity measurements were taken around the well of the K upland site. This area had a rather high soil porosity. The effective porosity of the soil is the difference between soil porosity and the wilting point moisture content. Soil effective porosity varied from about 0.45 to 0.15 $cm^3\ cm^{-3}$ in the profile down to 0.70 m in depth (Figures 4-29 and 4-30). The estimated effective porosity was 0.35, 0.30, 0.25, 0.20, 0.18, 0.15, 0.15 and 0.10 $cm^3\ cm^{-3}$ at depths of 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7 and >0.7 m, respectively, after integrating the published data (Phillips et al., 1989).

Based on the specific soil moisture change (*f*) at each layer, the following general equation was obtained for specific soil moisture yield S_{ys}:

$$S_{ys} = p\ f \tag{4-4}$$

with

$$f = \begin{cases} 1.9196\,WT - 1.1530\,WT^2 + 0.2058\,WT^3 & when \quad WT<1.25m \\ 1 & when \quad WT>1.25m \end{cases}$$

where p is the effective porosity, and WT is the water table depth, in *m*.

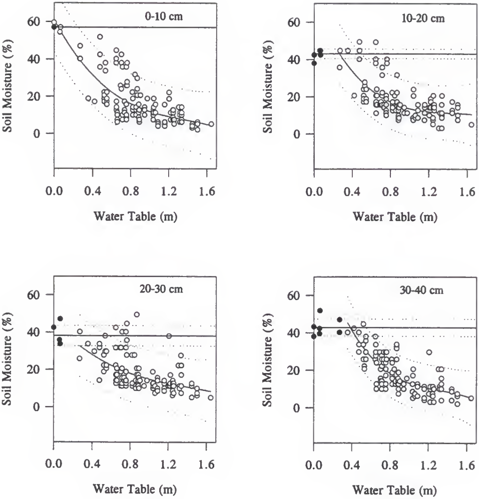


Figure 4-29. Relationship between soil moisture volumetric content and water table depth measured at depths 0-10, 10-20, 20-30 and 30-40 cm in the C, K, and N uplands. Solid circles are measured under saturated conditions. They are considered to be soil porosity measurements. The horizontal line is the average of the saturated soil moisture measurements.

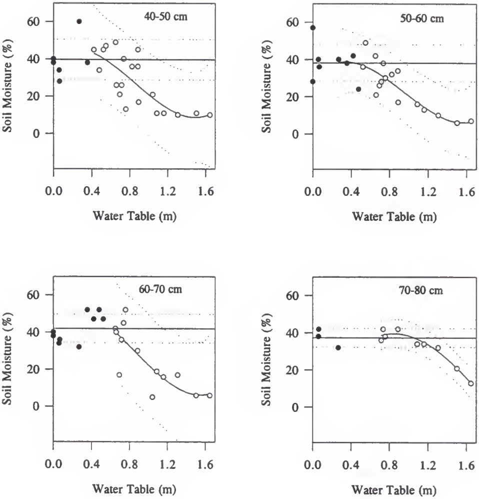


Figure 4-30. Relationship between soil moisture volumetric content and water table depth measured at depth 40-50, 50-60, 60-70 and 70-80 cm at the C, K and N uplands. Solid circles indicates saturated conditions. They are considered to be measurements of soil porosity. The horizontal line is the average of the saturated soil moisture measurements.

The estimated ET by White's equation (Eq. 2-1) is shown in Figure 4-31. A large variation was found in the daily ET estimates. Therefore, a model which accounts for the effects of previous rainfall and perhaps air entrapment and barometric pressure change is needed for the estimation of daily ET from water table fluctuations in uplands. The annual ET estimated by the method was 876, 1000 and 836 mm from the C, K and N uplands, respectively, with an average of 901 mm. These values were not significantly different from the simulation by the ETM as discussed later (see Table 5-7).

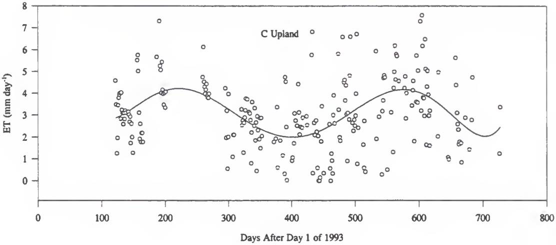


Figure 4-31. Daily evapotranspiration estimated from water table fluctuations at the C upland in 1993 and 1994.

CHAPTER 5
MODELING RESULTS AND DISCUSSION

Stomatal Conductance

Results

Multiple linear regression models (LIN) accounted for 22 and 33 percent of the variation of g_s for *P. elliottii* and *T. ascendens*, respectively (Table 5-1). The R^2 values were lower than those of the models for trembling aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh.) published by McCaughey and Iacobelli (1994). Although multiple nonlinear regression models (NLIN) were based on the same environmental variables as LIN, they explained much more variation. The R^2 values of NLIN models for *P. elliottii* and *T. ascendens* were 0.44 and 0.53, respectively.

Table 5-1. Results of forward stepwise multiple linear regression (LIN) analysis of g_s for the two tree species.

Species	Coefficient				r^2	p value
	a_0	a_1	a_2	a_3		
T. ascendens	-77.1	0.0465	-6.568	6.985	0.33	0.001
P. elliottii	-81.9	0.0302	-6.224	7.420	0.22	0.001

The NLIN equations obtained were:

T. ascendens:

$$g_s=397.70+18.108T-4.560VPD-31.289*\log(PAR)-293.021*\log(T)$$

$$+98.601*\log(VPD)+71.728*\frac{\sqrt{PAR}}{VPD+0.01}-61.879*\frac{\sqrt{PAR}}{VPD^2+0.01}$$

P. elliottii:

$$g_s=-1154.74+369.225*\log(T)-33.784*\log(VPD)-0.00000724*PAR^2$$

$$-0.05063*VPD^2+15.084*\frac{\sqrt{PAR}}{VPD+0.01}+1500.25*\frac{\sqrt{PAR}}{T^2}$$

The Jarvis model demonstrated a different behavior for the two species. It failed to converge for *T. ascendens* although different trials have been tried, including changing the initial values of the coefficients and the conditions for convergence. However, after changing the Michaelis-Menton constant b_0 to a variable depending on VPD, the modified Jarvis model (i.e., Jarvis') converged and accounted for 56 percent of the variation for *T. ascendens*. Both the Jarvis and Jarvis' models converged for P. elliottii and explained about 45 percent of the variation (Table 5-2). MIN11 models did not converge or the R^2 values were very small. This indicated that g_s was not controlled by one variable, but by multiple variables most of the time. The MIN21 model for *T. ascendens* also failed to converge, but the MIN22 models converged and had R^2 values of 0.52 and 0.43 for *T. ascendens* and *P. elliottii*, respectively (Table 5-2).

Table 5-2. Optimized coefficients of stomatal conductance models of *T. ascendens* and *P. elliottii* foliage. See text (p.38) for model structures.

Method	g_m	g_0	b_0	T_o	c_0	s_1	s_2	R^2
				T. ascendens				
MIN11[1]	49.8	1187.1	3786.0	26.1	0.4112	1.53	3.96	0.31
Jarvis[1]	98.2	1042.2	257.0	30.4	0.1535	0.30	0.00	0.50
MIN21[1]	161.8	8104.5	1667.2	29.6	0.3646	1.78	0.72	0.54
Jarvis'	129.5	7907.8	1131.5	29.6	0.3322	0.55	0.08	0.56
MIN22	144.9	7041.8	1119.7	29.7	0.4105	1.14	0.64	0.52
				P. elliottii				
MIN11	17.4	606.2	3692.1	44.0	0.1308	0.39	0.00	0.11
Jarvis	164.9	1705.3	88.6	31.3	0.2770	0.32	0.52	0.45
MIN21	123.3	3785.5	625.3	29.1	0.4533	0.90	0.34	0.45
Jarvis'	115.7	3611.4	247.7	29.7	0.4372	0.41	0.24	0.43
MIN22	114.7	3869.4	452.2	28.8	0.5145	0.80	0.26	0.43

---

[1] Did not converge

In all, multi-variate nonlinear models accounted for 52 to 56 and 43 to 45 percent of variation for *T. ascendens* and *P. elliottii*, respectively (Table 5-2). All the converging multiple variate models were statistically significant at the $p=0.001$ level. The differences between the measured and predicted g_s values by the various models have been shown in Figures 5-1 and 5-2.

Discussion

Stomatal conductances measured in this study covered a much wider range of conditions in time and space (six towers were used in total) than in other similar studies (Table 5-3). The amount of data used to build the stomatal conductance models was several times more than in similar studies published in the literature.

The Jarvis model performed differently for different species (Table 5-3). The explained variation varied from 18 percent in the subarctic marsh (Lafleur, 1988) to 73 percent for Douglas-fir (Jarvis, 1976). It accounted for 45 and 50 percent in the variation of g_s of slash pine and cypress (not converged), respectively, in the present study. Given the spatial and temporal scales covered in this research, the modeling results should be considered satisfactory.

The performance difference of the Jarvis and MIN21 models for these two species in terms of convergency may reflect the differences in stomatal response to the environmental conditions, because almost all measurements were taken alternately between species within an hour. On the other hand, it may also reflect that the Jarvis and MIN21 models are not general enough to apply to all species. McCaughey and Iacobelli (1994) also found that the Jarvis model failed to converge for their single canopy layer situation

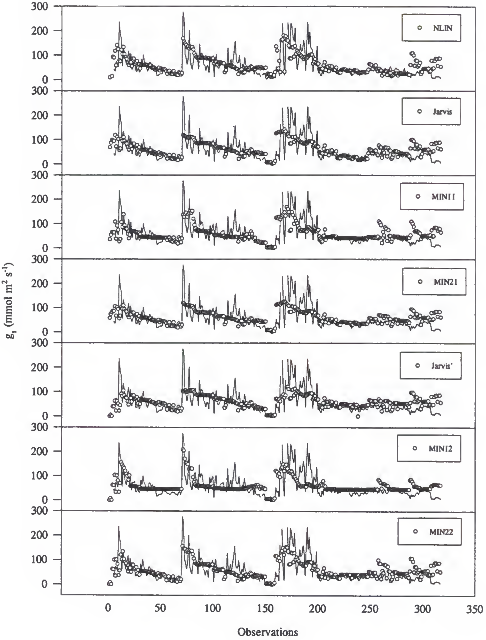


Figure 5-1. Comparison of simulated and measured stomatal conductance of *T. ascendens*. Solid line indicates measurements, while circles are predicted values.

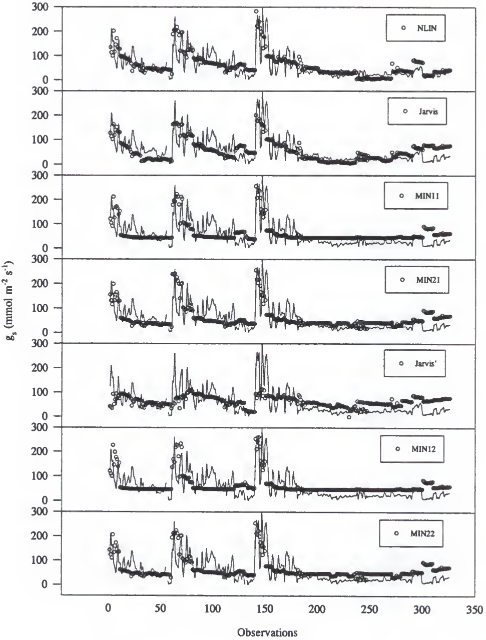


Figure 5-2. Comparison of simulated and measured stomatal conductance of *P. elliottii*. Solid line indicates measurements, while circles are predicted values.

Table 5-3. Comparison of the performance of Jarvis type of stomatal conductance model.

Species	n	r^2	Source	Notes
Carex paleacea	197	0.32	Lafleur, 1988	Subarctic marsh, 14 June - 12 August, 1985.
Alnus rugosa	117	0.18	Ibid	Ibid
Salix bebbianna	117	0.18	Ibid	Ibid
Salix discolor	117	0.23	Ibid	Ibid
Populus tremuloides		0.47	MaCaughey and Iacobelli, 1994	19-21 m (middle canopy); 18 July - 27 September
Betula papyrifera		0.39	Ibid	Ibid
Picea sitchensis	80	0.51	Jarvis, 1976	Upper canopy, 25 April - 17 May, 1973
Pseudotsuga menziesii	113	0.73	Ibid	Middle canopy, 8 August - 11 September, 1973
Taxodium ascendens	623	0.50	This study	Full canopy; May 1993 to January 1994
Pinus elliottii	637	0.45	This study	Ibid

when the effect of temperature was included, which they attributed to overparameterization of the model.

Multiple nonlinear models explained approximately the same amount of variation, but what made the Jarvis and MIN21 types of models better than the NLIN models was that they incorporated a number of physiologically meaningful parameters, such as g_0, g_m, b_0, and T_o. Optimal temperatures for the two species in this study were about the same at about 30 °C. If PAR and T were at optimal values and VPD approached zero, stomatal conductance (g_s) would approach g_0. Or, if PAR and T were at optimum values and VPD increased, stomatal conductance (g_s) would approach g_m. Minimum potential g_s values were approximately the same for both species (Table 5-2). However, g_0, b_0 and a_0 were quite different. By comparing these parameters, it can be seen that g_s of *T. ascendens* changed more gradually with a change of PAR (with a relative higher b_0) and VPD (with higher g_0 and smaller decay coefficient a_0) than that of *P. elliottii*.

In addition to there being no physiological meaning in the coefficients obtained from multiple regression, the resultant equations could also produce negative predictions of g_s for both species (see Figures 5-1 and 5-2). However, these models could be improved if lower boundary values were set for these species.

Rainfall Interception

The interception model was run on an hourly basis, but the comparison of predicted and measured rainfall interception was made on a weekly basis because of the time scale of the available rainfall interception information data. The predicted weekly sums agreed well with the measurements (Figures 5-3 and 5-4).

This new model was compared with other models using data from the literature (Gash, 1979; Hutjes et al., 1990; Lankreijer et al., 1993; Table 5-4). All variables except D were available in the original papers. The average dryness index D during the period of interest (T) was estimated by the average rainfall amount per storm (i.e., P divided by n). The evaporation rate during rainfall was estimated by the authors either from interception measurements or from the Penman-Monteith equation. The prediction was performed on both a daily basis (assuming only one storm per rainy day) and on a storm event basis. By using information published by Gash (1979) for all small (not enough to saturate the canopy) and big events, the 256 mm predicted by the new model was the same as that predicted by the Gash model at 257 mm. The prediction based on the new model was better than that by the Mulder model. The new model performed better on an event basis than on a daily basis. This was illustrated with the data from the Ivory Coast (Hutjes et al., 1990; Table 5-4). The predicted interception was very close to the measured interception (Table 5-4). In terms of simplicity and data requirements, the new model was the simplest, followed by the Gash model, and then the Mulder model.

The new interception model derived in this study is a general model of rainfall interception without empirical parameters. All parameters including canopy storage capacity C_m, canopy dryness index D and canopy openness b_0 have specific physical meanings. Many empirical models are special cases of this model (Table 5-5):

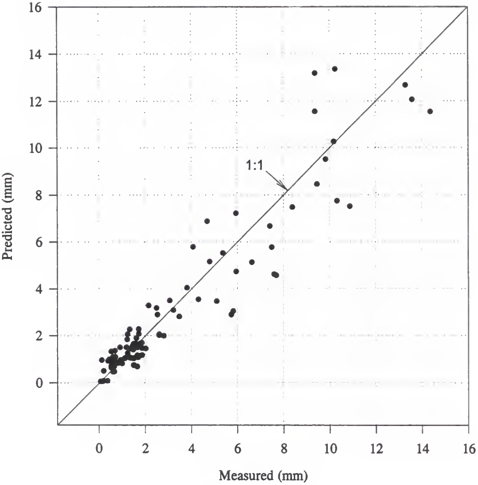


Figure 5-3. Comparison of predicted and measured rainfall interception on a weekly basis (R^2=0.89).

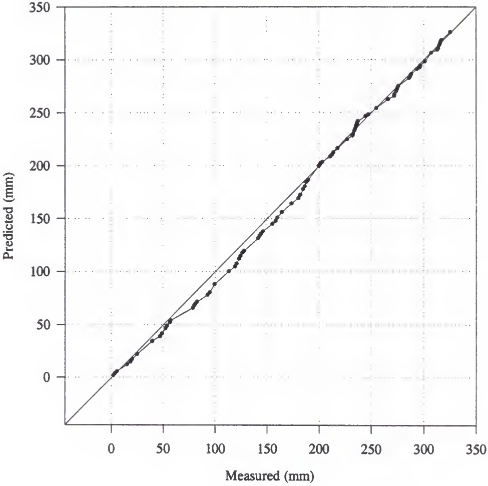


Figure 5-4. Comparison of cumulative predicted and measured rainfall interception in all six cypress wetlands and slash pine uplands.

Table 5-4. Comparison of predicted rainfall interception using the Gash, Mulder and new Liu model.

P	n	C_m	$1 - b_0$	R	e	D	I_m	Liu	Gash	Mulder	Location	
822	132	0.8	0.68	1.38	0.19[1]	0.005	245	256	257		East Anglia[3]	Gash, 1979 (Event basis)
73.7	161	0.8	0.68	1.38	0.19[1]	0.678						
370	85	0.26	0.57	1.26	0.1[2]	0	46.3	56.1	47.5	66	Les Landes, France[3]	Lankreijer et al., 1993
370	85	0.26	0.57	1.26	0.09[1]	0	46.3	47.9	44.7			
209	50	0.7	0.69	1.89	0.16[2]	0.016	37.6	50.3	43.3	59.6	Ede, Netherlands[3]	
209	50	0.7	0.69	1.89	0.15[1]	0.016	37.6	49.2	44.3			
102	38	0.5	0.69	1.78	0.24[2]	0.025	23.2	30.6	25.1	27.2	Ede, Netherlands[3]	
102	38	0.5	0.69	1.78	0.14[1]	0.025	23.2	25.6	26.2			
1022	128	0.61	0.97	20	0.34[1]	0	94	94.2		85.7	Ivory Coast[4]	Hutjes et al., 1990
1022	128	0.61	0.97	20	0.18[2]	0	94	86.7				
1022	77	0.61	0.97	20	0.34[1]	0	94	63.6	61.7		Ivory Coast[3]	
1022	77	0.61	0.97	20	0.18[2]	0	94	55.9	53.6			

[1] Mean evaporation rate estimated from interception measurements.

[2] Mean evaporation rate as calculated with the Penman-Monteith formula.

[3] Daily basis.

[4] Event basis.

Table 5-5. Comparison of some interception models

Liu model :

$$I = C_m \cdot D_0 \cdot [1 - \exp(-(1-b_0)P/C_m)] + \int_0^T e_w \cdot [1 - D_0 \exp(-(1-b_0)P/C_m)] \cdot dt$$

Horton (1919):

$$I = C_m + e_w \cdot T$$

Linsley et al. (1949):

$$I = C_m(1-\exp(-\delta \cdot P)) + e_w \cdot T(1-\exp(-\delta \cdot P))$$

Merriam (1960):

$$I = C_m \cdot (1-\exp(-P/C_m)) + e_w \cdot T$$

Aston (1979):

$$I = C_m \cdot (1-\exp(-kP/C_m)) + e_w \cdot T$$

Calder and Newson (1979):

$$I = \gamma \cdot (1-\exp(-\delta P))$$

Calder (1986):

$$I = C_m(1-k' \cdot \exp(-q \cdot P/c_m)) + e_w \cdot T$$

☞ When assuming a) the canopy dryness index before any rainfall event is one ($D_0=1$), and b) evaporation from the canopy during rainfall proceeds at a rate as though the canopy is totally saturated, the general model decays to Horton's model (1919).

☞ Linsley's model (1949; $1\text{-}b_0=1$, $D_0=1$) can be derived from the general model by assuming a) the canopy is totally dry before each rainfall event ($D_0=1$), and b) the canopy is fully closed and has no gaps ($b_0=0$).

☞ Merriam's model (1960) is the special case where a) the canopy is totally dry before each rainfall event ($D_0=1$), b) the canopy is fully closed ($b_0=0$), and c) evaporation from the canopy during rainfall proceeds at a rate as though the canopy is totally saturated. In other words, the canopy wetness and its effect on evaporation have not been considered.

☞ Aston (1979) experimentally found that surface storages of eight small trees could be described by:

$$C = C_m \cdot (1 - \exp(-kP/C_m)) \qquad (5\text{-}1)$$

Aston (1979) recognized that the k value is "the proportion of rainfall intercepted and conceptually should equal 1 - p " (p is free throughfall coefficient). It was demonstrated that k and 1-p were in good agreement except for *Pinus radiata*.

☞ An empirical model was proposed to predict daily rainfall interception (Calder and Newson, 1979; Newson and Calder, 1989; Calder, 1990). The exponential expression embedded in the model was identical to the other models. However, it merged the storage part and evaporation part into on single expression. By comparing Calder and Newson's model with Linsley's, it can be seen that the empirical parameter γ equals (C_m+e_wT). Clearly, γ is not a constant on an event basis.

Transpiration, Canopy Conductance and the Coupling of a Forest with the Atmosphere

Verification of the Transpiration Model

The water vapor fluxes measured by the eddy covariance method in another on-going research project in the area led by Dr. Gholz and Dr. Cropper were used to verify the transpiration submodel. The values predicted for their dense and mature pine forest stand agreed well with the measurements obtained by the eddy covariance method (Figure 5-5). The discrepancy some times between the predicted and the measured was probably caused by the buoancy of the area (footprint) sensed by the Eddysol System.

Transpiration and Conductance at the Canopy Level

In this section, the results for the C upland and the C wetland will be mainly presented, as the other sites demonstrated similar results.

Daily pattern

The daily patterns of PAR, VPD, temperature and canopy dryness index of a day in each 30-day interval have been shown in Figure 5-6. These days were selected to represent the daily patterns of the environmental variables during different seasons. It can be seen from the fluctuations of the canopy dryness index that there was rainfall on days 90, 180, 240, 270 and 330. Rainfall occurred on the days previous to days 150, 180 and 240 because the canopy was wet in the early morning. Clouds appeared on days 30, 120, 150 and 240 because PAR fluctuated considerably during these days.

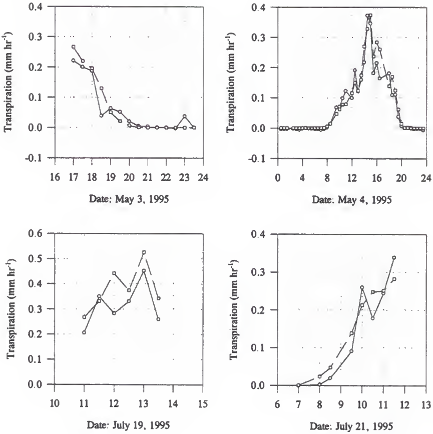


Figure 5-5. Comparison of the predicted (☐) and measured (O) transpiration using the eddy covariance method for a slash pine plantation.

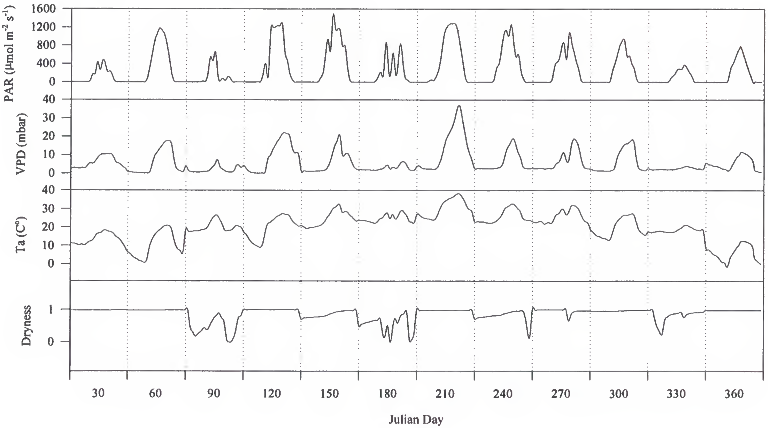


Figure 5-6. Daily patterns of photosynthetically active radiation, vapor pressure deficit, temperature and canopy dryness index in the C wetland during 1993.

Canopy conductance g_c increased rapidly in the early morning with increasing PAR in cypress wetlands (Figure 5-7) as well as slash pine uplands (Figure 5-8). It generally peaked in the morning. This pattern agreed with the observed pattern of stomatal conductance at the leaf level, and for other forests (e.g., Lindroth, 1985). The magnitude of its daily fluctuations was a function of PAR, VPD, temperature and LAI (Figure 5-9).

The daily pattern of transpiration was similar to that of g_c, but in contrast, it generally peaked in the early afternoon (Figures 5-7 and 5-8).

Transpiration, g_c, and g_b were higher in the C upland than in the C wetland because of the difference in LAI, although they presented a similar daily pattern (Figures 5-7 and 5-8). The aerodynamic conductance g_a between the effective source plane and the reference height was similar for both uplands and wetlands.

The canopy-atmosphere coupling factor $1\text{-}\Omega$ decreased with the increase of PAR in the early morning, when PAR changed faster than VPD or temperature (Figure 5-10). Thereafter, $1\text{-}\Omega$ increased steadily until the canopy was coupled again with the overhead atmosphere in the evening. Its daily course was very similar to that of g_c (Figures 5-7 and 5-8). There was no significant difference between the wetland and the upland with respect to $1\text{-}\Omega$ during these days.

Seasonal pattern

Maximum radiation occurred in May when there was more sky clarity than during the rest of the growing season (Figure 5-11). Temperature and VPD peaked in late July at about 32°C and 25 mbar, respectively. The seasonal variation of radiation, temperature

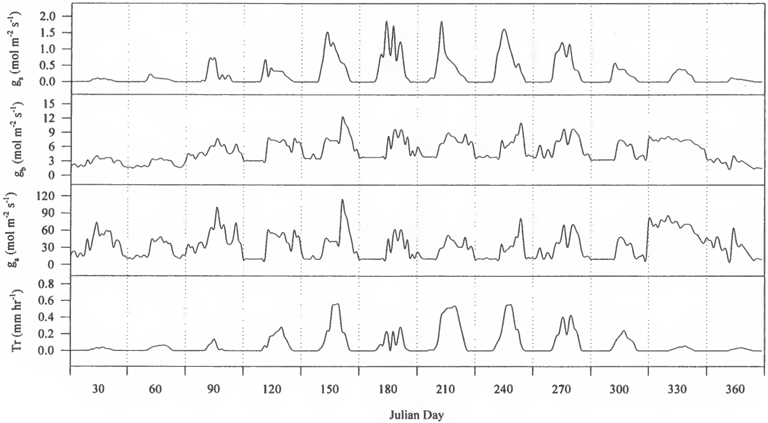


Figure 5-7. Daily patterns of canopy conductance, leaf boundary-layer conductance, aerodynamic conductance and transpiration in the C wetland during 1993.

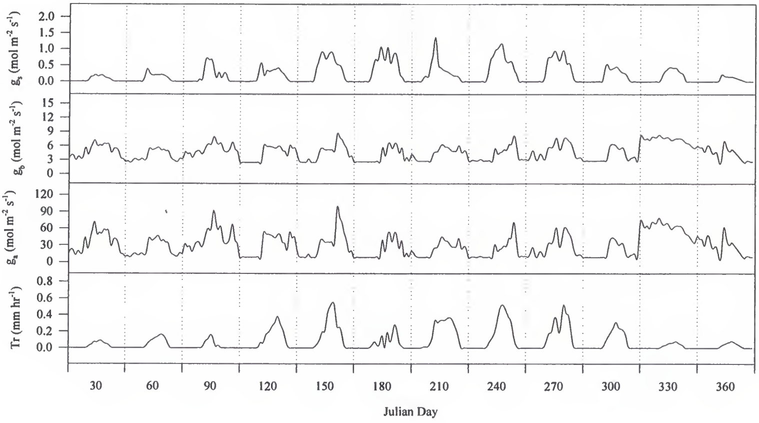


Figure 5-8. Daily patterns of canopy conductance, leaf boundary-layer conductance, aerodynamic conductance and transpiration in the C upland during 1993.

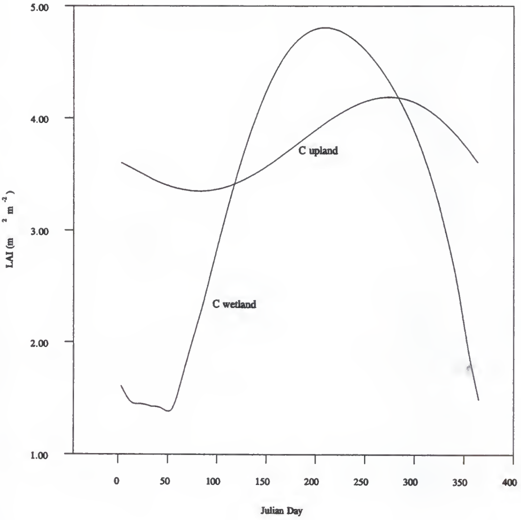


Figure 5-9. Temporal change of leaf area index in the C wetland and C upland during 1993.

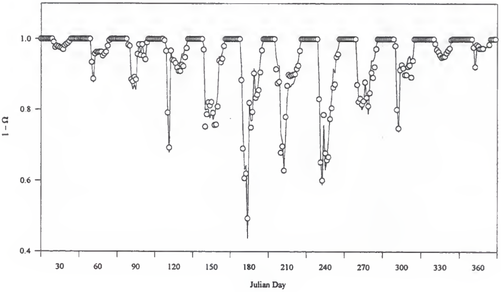


Figure 5-10. Daily pattern of canopy-atmosphere coupling factor in the C wetland (line) and C upland (circles) during 1993.

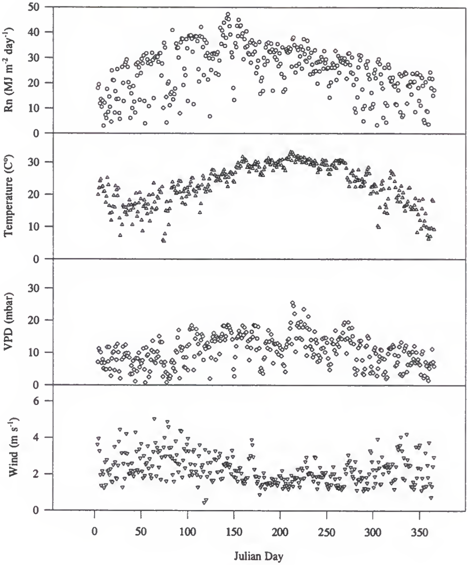


Figure 5-11. Seasonal variation of net radiation, temperature, vapor pressure deficit and wind velocity during 1993.

and VPD showed higher values in summer time and lower values during the winter. Higher wind speeds occurred during the spring and winter seasons.

The temporal change of LAI showed a different pattern between the C upland and the C wetland (Figure 5-9). LAI peaked at 4.7 m^2 m^{-2} in July in the wetland, and at 4.2 m^2 m^{-2} in September in the upland. Minimum LAI was just before the beginning of the growing season with a value of 1.4 and 3.4 m^2 m^{-2} in the wetland and upland, respectively. The LAI in the wetland did not go to zero because of the presence of pine trees among the deciduous cypress trees.

Maximum g_c occurred in July and September in the C wetland and upland, respectively (Figure 5-12). This pattern agreed with the seasonal pattern of LAI at these sites (Figure 5-9). Canopy conductance (g_c) in the C wetland was higher than that in the upland, but the relationship reversed during the winter months. This was consistent with the dynamic difference of LAI between these two ecosystems.

Transpiration reached its maximum value in May (around Julian Day 150) when maximum net radiation peaked (Figure 5-13). Transpiration was reduced in July (around Julian day 200) due to the appearance of low VPD and low wind speed conditions. The latter decreased the leaf boundary-layer conductance and also canopy aerodynamic conductance (Figures 5-14 and 5-15).

The seasonal change of the canopy-atmosphere decoupling factor Ω demonstrated a very similar pattern in both the C wetland and the C upland (Figure 5-16). The canopies were maximally decoupled from the atmosphere overhead during June, and well coupled in the winter months.

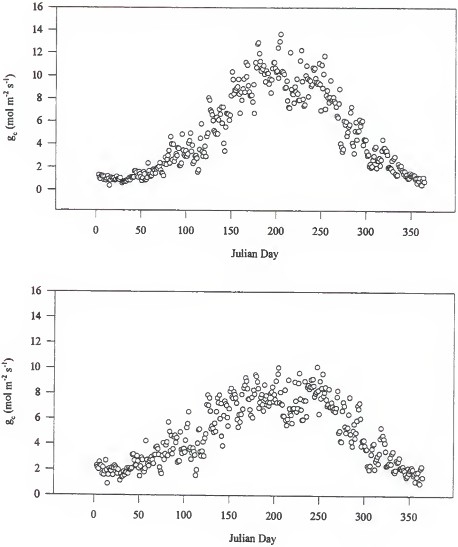


Figure 5-12. Seasonal change of canopy stomatal conductance in the C wetland (upper panel) and C upland (lower panel) during 1993.

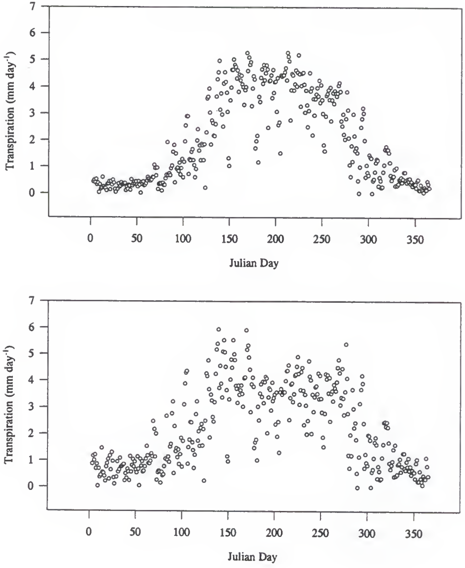


Figure 5-13. Seasonal change of transpiration in the C wetland (upper panel) and C upland (lower panel) during 1993.

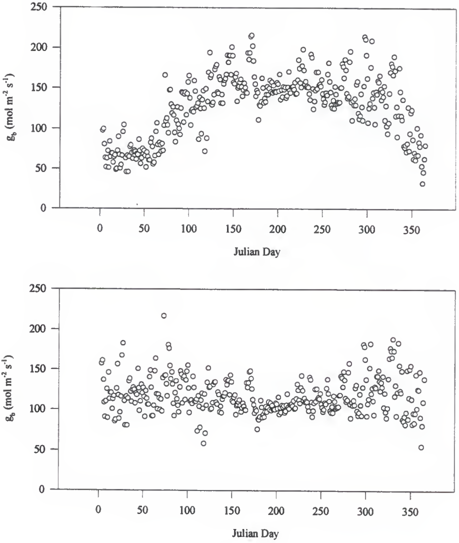


Figure 5-14. Seasonal variation of total leaf boundary-layer conductance in the C wetland (upper panel) and C upland (lower panel) during 1993. Data presented is the sum of the 24 hourly data of a day.

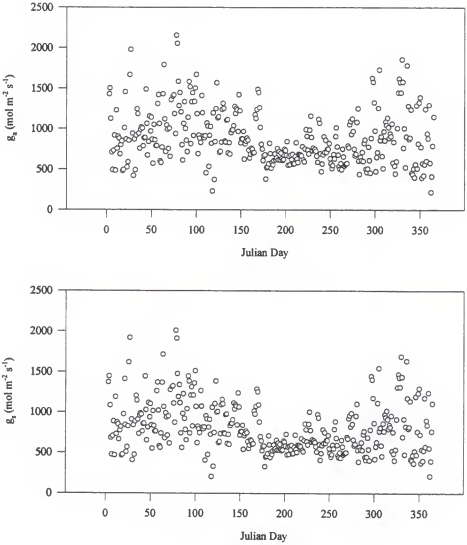


Figure 5-15. Seasonal variation of aerodynamic conductance in the C wetland (upper panel) and C upland (lower panel) during 1993. Data presented is the sum of the 24 hourly data of a day.

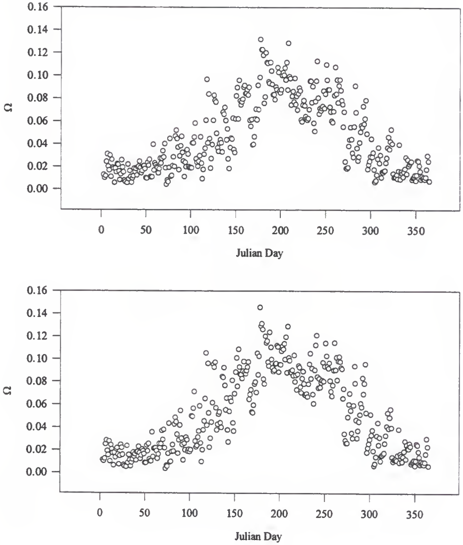


Figure 5-16. Daily canopy-atmosphere decoupling factor in the C wetland (upper panel) and C upland (lower panel) during 1993. Data presented are the hourly averages.

Comparison Among Transpiration Submodels

Although both the multi-layer Penman-Monteith model (MPM) and the general combination equation (GCE) (Lhomme, 1988b) were derived from the concept of electric flow, there was some difference as to the number of elementary conductances involved.

The whole canopy was considered to be one single "big leaf" when the Penman-Monteith equation was applied to a single layer canopy. Transpiration was assumed to take place at a certain plane in the canopy. The aerodynamic conductance or boundary-layer conductance of the canopy was calculated from the water vapor flux from this plane to the reference plane above the canopy. The canopy conductance was equal to stomatal conductance, but weighted by LAI (e.g., Jarvis and Morison , 1981). However, it has been shown both theoretically (Stewart and Thom, 1973; Paw U and Meyers, 1989) and experimentally (Baldocchi et al., 1987) that the canopy conductance derived from this "top-bottom" method contained additional non-physiological information pertaining to the net radiation balance and the aerodynamic conductance inside the canopy (Baldocchi et al., 1991; Lhomme, 1991).

For multiple-layer canopy situations, the Penman-Monteith equation was applied at the leaf level first and then scaled up to the canopy level by assuming that individual leaves act independently. Therefore, the aerodynamic conductance was equated to the leaf boundary-layer conductance. The aerodynamic conductance beyond the leaf boundary-layer was not considered (e.g., Jarvis and Morison, 1981; Roberts et al., 1993). This "bottom-up" method is very easily applied to a canopy with multiple layers, such as in forests (e.g., Roberts et al., 1993).

The aerodynamic conductance from one layer to another has been ignored in the MPM. The reason why this treatment is acceptable in most practical cases is because the major non-biological conductance that restricts water vapor from moving away from forests is the leaf boundary layer conductance. In contrast, for the development of GCE the between-layer conductance has been considered as one of the elementary conductances which vapor molecules experience on the way out of the canopy. Therefore GCE is more theoretically sound than MPM and therefore has been judged to be the most accurate transpiration submodel for this study.

The simulated results of MPM were systematically higher than those of GCE (Table 5-6), but they were not significantly different. The maximum difference between MPM and GCE was only 32 mm or 6 percent of the annual transpiration at all sites in three years. This suggests that the between-layer conductance had little influence on the transpiration process that occurred in the cypress wetlands and slash pine uplands in Florida flatwoods.

Hysteresis in the Change of Environmental Variables

In the early morning, radiation, VPD and temperature tended to be the lowest during the day. As the sun rose, solar radiation increased, so did VPD and air temperature. Solar radiation reached its maximum at solar noon. However, temperature and VPD still kept increasing even when the radiation remained the same or decreased some. Only later in the afternoon when radiation decreased significantly, did the temperature and VPD also decrease. Because of the temperature build-up in the morning and early afternoon, this relationship with PAR in the afternoon proceeded along a

Table 5-6. Comparison of annual transpiration (mm) predicted by different models.

Plot		1991			1992			1993		
		MPM[1]	GCE[2]	Diff.	MPM	GCE	Diff.	MPM	GCE	Diff.
Upland	C	597	565	32	610	574	36	673	644	29
	K	548	528	20	560	537	23	620	603	17
	N	512	487	25	525	496	29	578	556	22
	Mean	552	527	26	565	536	29	624	601	23
Wetland	C	514	505	9	519	504	15	590	585	5
	K	430	422	8	433	420	13	502	495	7
	N	577	560	17	579	556	23	655	643	12
	Mean	507	496	11	510	493	17	582	574	8

[1] MPM = multi-layer Penman-Monteith model

[2] GCE = General Combination Equation

afternoon proceeded along a different pathway than that in the morning (Figure 5-17). In other words, the relationship between PAR and temperature or VPD was not linearly reversible, and depended on the time of the day. The rising and falling limbs together formed a loop. This decoupling of environmental variables, or hysteresis, is very important in understanding the hourly variation of stomatal and canopy conductance and transpiration during the day.

Hysteresis in the Responses of Transpiration and Stomatal Conductance to Environmental Variables

To demonstrate the relationship between canopy conductance or transpiration and environmental variables more clearly, days 30, 120, 210 and 300 of the different seasons of 1993 were used. There was no rainfall on these days (Figure 5-6). Apparent decoupling loops existed in the relationship between PAR and canopy conductance during these days (Figure 5-18). Three stages could be identified:

1) In the early morning, when VPD was low, the canopy conductance increased rapidly with PAR .

2) With increasing VPD, it became the main controlling factor of canopy conductance. After reaching this stage, the increase of PAR generally showed a proportional increase of VPD, which led to the apparent decrease of canopy conductance with increasing PAR (e.g., day 210 in Figure 5-18). However, if VPD did not get high enough to become the major controlling factor, the g_c - PAR loop would be less apparent as demonstrated by day 30 (Figure 5-18).

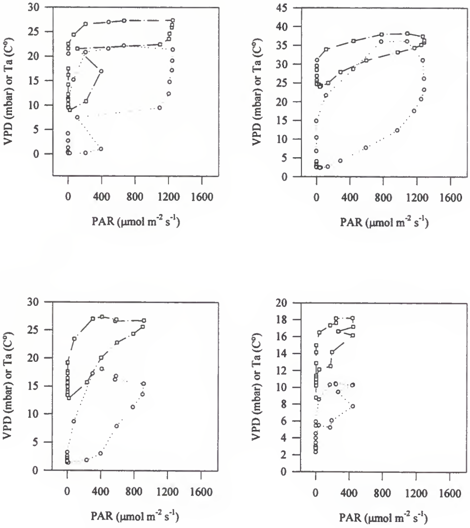


Figure 5-17. Relationship between photosynthetically active radiation and vapor pressure deficit (circles) and temperature (squares) on days 120 (upper-left), 210 (upper-right), 300 (lower-left) and 30 (lower-right) of 1993.

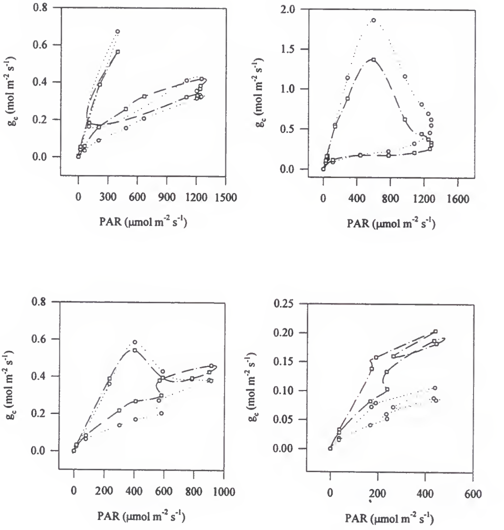


Figure 5-18. Relationship between photosynthetically active radiation and canopy conductance at C wetland (circles) and C upland (squares) on days 120 (upper-left), 210 (upper-right), 300 (lower-left) and 30 (lower-right) of 1993.

3) At the third stage, canopy conductance g_c decreased faster with PAR than the rising rate in the first stage because of the stronger co-effects from other variables such as VPD. This is the direct result of the decoupled change of PAR and other variables.

The transpiration - PAR or Tr - PAR loops were not as apparent as g_c - PAR loops (Figure 5-19). In the first stage of the g_c - PAR loop, g_c increases very fast with PAR. However, the increase of transpiration was not as fast as that of g_c due to a low VPD at this stage. After PAR reached its maximum, the increase of VPD led to an increase of transpiration. This corresponded to the second stage of the g_c - PAR loop, but there were two differences with the second stage of the Tr - PAR loop. First, the second stage appeared later in the Tr - PAR loop than in the g_c - PAR loop. The former appeared after PAR reached its maximum, while the latter appeared when the VPD effect on g_c became the strongest, which generally occurred in the morning. The other difference is the direction of the loops. Although transpiration was controlled by both g_c and VPD, the decrease of g_c was not large enough to offset the effect of the VPD increase due to the fact that g_c decreased exponentially with the increase of VPD. The Tr-PAR loop was counter-clockwise, while the g_c-PAR was clockwise (Figures 5-18 and 5-19).

Daily transpiration increased linearly with g_c in the C wetland and upland (Figure 5-20). If we consider it as a diffusion process following Fick's law, we can see that transpiration (T_r) depends on at least the VPD and g_c. For a given g_c, transpiration may change with VPD, i.e., the lower the VPD, the lower the transpiration. However, this relationship contained variation.

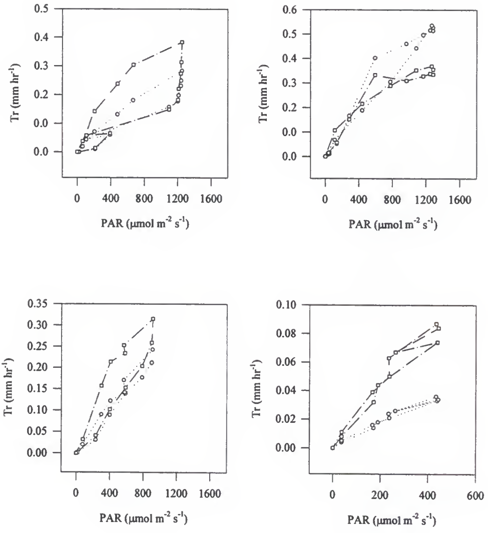


Figure 5-19. Relationship between photosynthetically active radiation and transpiration in the C wetland (circles) and C upland (squares) on days 120 (upper-left), 210 (upper-right), 300 (lower-left) and 30 (lower-right) of 1993.

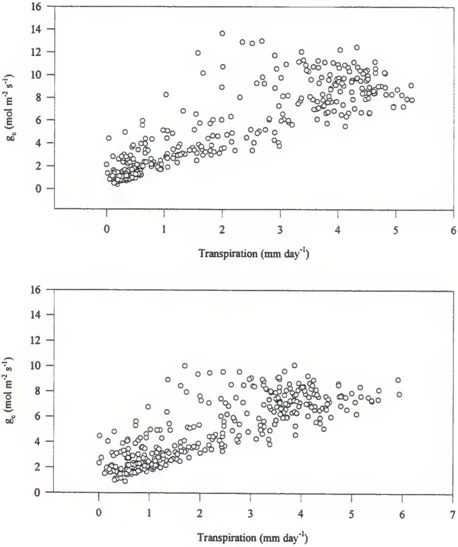
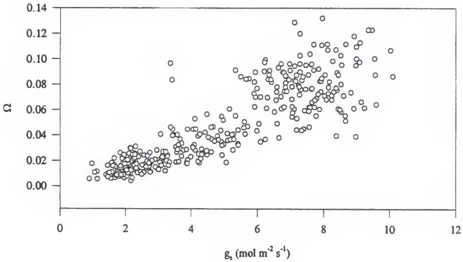


Figure 5-20. Relationship between canopy conductance (the sum of 24 hourly data of a day) and transpiration in the C wetland (upper panel) and C upland (lower panel) during 1993.

Degree of the Canopy-Atmosphere Coupling

A stronger linear relationship was found between g_c and the canopy-atmosphere decoupling factor Ω (Figure 5-21) than the relationship between transpiration and Ω (Figure 5-22). However, the decoupling factor Ω was really determined by the ratio of g_a and g_c, or canopy aerodynamic conductance to canopy stomatal conductance (Figure 5-23). The canopy was better coupled with the atmosphere as the ratio increased. This was consistent with the theoretical consideration for the original equation used to calculate Ω, where for two ecosystems standing side by side and having the same characteristics except canopy conductance, the ecosystem with the higher canopy conductance would be more decoupled from the atmosphere overhead. For a canopy, the diurnal change of Ω is very much correlated with the change of g_c. This is because the diurnal pattern of g_a is usually not apparent.

Pine uplands demonstrated a different relationship between Ω and LAI as compared to cypress wetlands (Figure 5-24). The species composition of wetlands was dominated by deciduous tree species such as pond cypress and black gum, which differed from upland evergreen species with slash pine in the overstory and saw palmetto in the understory. Although all tree species leafed out at about the same time in the spring, the leaves of deciduous species expanded much faster than the pine needles. Cypress leaves reached their maximum expansion at an earlier time (July) than the pine needles (September). The difference was in accordance with other observations in this area (Gholz et al., 1991). Because of the difference in the temporal change of LAI in uplands and wetlands and the seasonal variation of g_c (Figure 5-12) and g_a (Figure 5-15), these two ecosystems had a



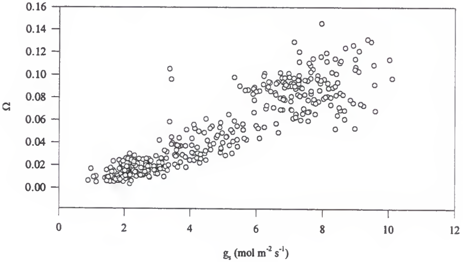


Figure 5-21. Daily average of canopy-atmosphere decoupling factor as a function of canopy stomatal conductance in the C wetland (upper panel) and C upland (lower panel) during 1993.

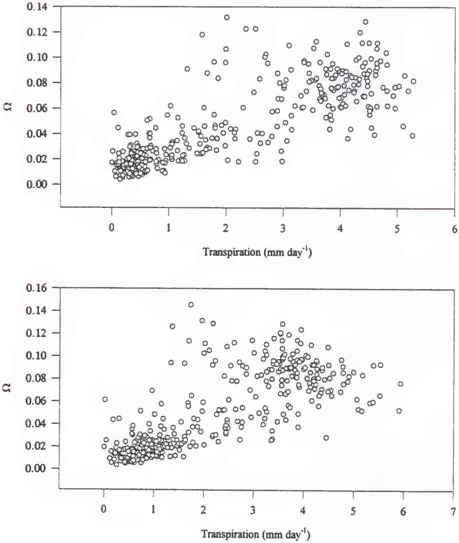


Figure 5-22. Daily average of canopy-atmosphere decoupling factor as a function of transpiration in the C wetland (upper panel) and C upland (lower panel) during 1993.

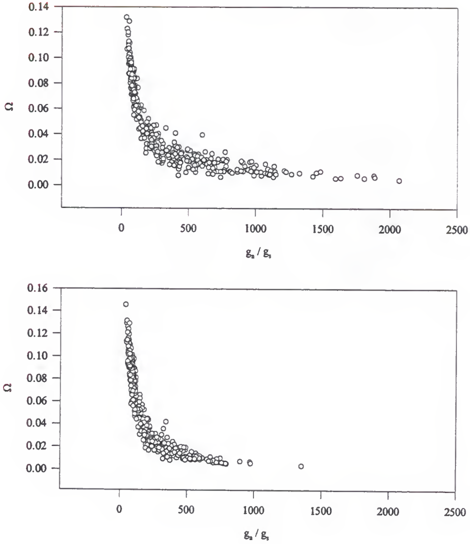


Figure 5-23. Daily average of canopy-atmosphere decoupling factor as a function of the ratio of aerodynamic conductance and canopy stomatal conductance in the C wetland (upper panel) and C upland (lower panel) during 1993.

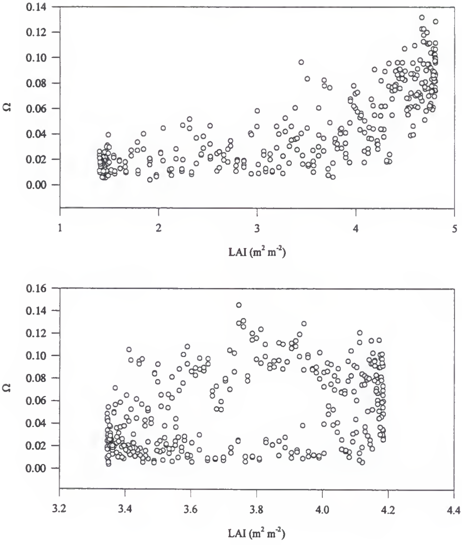


Figure 5-24. Daily average of the canopy-atmosphere decoupling factor Ω as a function of leaf area index in the C wetland (upper panel) and C upland (lower panel) during 1993.

very different relationship between Ω and LAI. The decoupling factor Ω increased slowly with the increase of LAI when LAI was smaller than 4 m^2 m^{-2} in the wetlands, but it increased much faster with increasing LAI beyond this value (Figure 5-24).

The relationship between LAI and Ω in the uplands formed a clockwise loop beginning at LAI 3.6 m^2 m^{-2} at the start of the year (Figure 5-24). LAI gradually decreased to a minimum because of needle fall and no new growth until April. The decoupling factor Ω reached its maximum in July when LAI was around its average. This kind of loop relationship between LAI and Ω was a direct result of the de-synchronization of LAI and Ω.

The absolute relationship between Ω and LAI is determined by the characteristics of the species (e.g., stomatal conductance and its relationship with its controlling variables), ecosystem (e.g., species composition, spatial and temporal change of LAI) and the climate of the area, because g_c and g_a as the two main determinators of Ω, are characterized by some or all of these factors.

Evapotranspiration from Cypress Wetlands and Slash Pine Uplands

Comparison of ET in Time and Space

There was no significant difference in annual transpiration between pine uplands and cypress wetlands from 1991 to 1993 (Table 5-7). The average of the nine plot-year data was 521 and 554 mm in the wetlands and the uplands, respectively. There was no significant difference between years from 1991 to 1993. The temporal variation of

Table 5-7. Transpiration, rainfall interception, substrate evaporation and total ET From Florida flatwoods ecosystems.

Item	Year	Cypress Wetland					Pine Upland				
		C	K	N	Mean	Std.Err.	C	K	N	Mean	Std.Err.
Transpiration	1991	505	422	561	496	40	565	529	487	527	23
	1992	504	420	557	494	40	573	536	496	535	22
	1993	585	495	643	574	43	644	603	556	601	25
	Mean	531	446	587	521	41	594	556	513	554	23
	Std.E.	27	25	28	27		25	24	22	23	
Interception	1991	256	236	292	261	16	227	211	182	207	13
	1992	297	270	337	301	19	267	247	215	243	15
	1993	236	212	260	236	14	216	201	172	196	13
	Mean	263	239	296	266	17	237	220	190	215	14
	Std.E.	18	17	22	19		15	14	13	14	
Substrate E.	1991	6	159	55	73	45	18	44	11	24	10
	1992	302	387	310	333	27	22	38	10	23	8
	1993	110	228	118	152	38	26	48	11	28	11
	Mean	139	258	161	186	37	22	43	10	25	10
	Std.E.	87	67	77	77		2	3	0	1	
Total ET	1991	767	817	908	831	41	810	784	680	758	40
	1992	1103	1077	1204	1128	39	862	821	721	801	42
	1993	931	935	1021	962	29	886	852	739	825	44
	Mean	934	943	1044	974	35	852	819	713	795	42
	Std.E.	97	75	86	86		22	20	17	20	

transpiration, indicated by the temporal standard deviation, was less than its spatial variation in the wetlands. The temporal and spatial standard deviation of transpiration in the wetlands were ±27 and ±41 mm, respectively, but those in the uplands were the same at ±23 mm. Transpiration from the N wetland (587±28 mm) was significantly higher than that from the K wetland (446±25 mm).

The nine plot-year averages of rainfall interception were 266 and 215 mm at wetlands and uplands, respectively (Table 5-7). The difference of 51 mm was not significant. The spatial variation was not significantly different from the temporal variation. The temporal and spatial standard deviations were ±19 and ±17 mm in the wetlands, and ±14 and ±14 mm in the uplands, respectively. There was no significant difference with respect to interception between the different sites of wetlands and uplands and between different years.

Evapotranspiration (ET), or the sum of transpiration, interception and substrate evaporation, from these three wetlands from 1991 to 1993 averaged 974±86 mm, which was not significantly more than that from their adjacent slash pine uplands with an average of 795±20 mm (Table 5-7). The spatial variation was smaller than temporal variation of ET in the wetlands, while the opposite held true in the uplands. The highest annual ET was in the N wetland with a value of 1044 mm, while the lowest was in the N upland with a value of 713 mm. These two sites also had the highest and lowest LAI, respectively. Evapotranspiration accounted for 73 and 60 percent of the rainfall in the cypress wetlands and in the slash pine uplands, respectively (Table 5-8).

Table 5-8. Annual evapotranspiration in percent of annual rainfall.

year	Cypress Wetlands					Pine Uplands					Rainfall
	C	K	N	Mean	Std. Err.	C	K	N	Mean	Std. Err.	(mm)
1991	61	65	72	66	3	64	62	54	60	3	1260
1992	84	82	92	86	3	66	63	55	61	3	1312
1993	65	66	72	67	2	62	60	52	58	3	1426
Mean	70	71	79	73	3	64	62	54	60	3	1333

There was no significant difference in ET between wetlands and uplands during 1991 and 1993, but evapotranspiration from the wetlands was significantly higher than that from uplands during the wet year of 1992. Evaporation from open water surfaces was 73, 333 and 152 mm in 1991, 1992 and 1993, respectively (Table 5-7). Therefore evaporation from the standing water surfaces in wetlands was the primary determinant of the difference in ET between the wetlands and the uplands at these particular sites.

Sensitivity Analysis

It is important to know the changes of ET under various environmental conditions, including different LAI, solar radiation, relative humidity and air temperature levels. The water level fluctuations in the K wetland during the wet year of 1992 and the meteorological information of 1993 (which had less missing data) were used for the following sensitivity analysis of the ETM model. The leaf area index (LAI) was expressed as the peak LAI of the stands during the year.

Leaf area index was an important factor in controlling ET (Figure 5-25). Evapotranspiration increased at a steadily decreasing rate with the increase of LAI. It approached a limit after the LAI was 10 m^2 m^{-2}. The difference of the ET-LAI relationships between cypress wetlands and pine uplands was nearly constant over a wide range of LAI. The difference was mainly dictated by the magnitude of evaporation from the water surface in the wetlands. If the evaporation from wetlands had been half the potential rate, then there would have been no difference in ET between these two ecosystems.

Evapotranspiration from cypress wetlands was more sensitive to a change in radiation than ET from pine uplands (Figure 5-25 and Table 5-9). That may be a result of the ecological adaption of a vertical distribution of cypress leaves in this region.

Evapotranspiration from both ecosystems was also quite sensitive to a change in air temperature (Table 5-9). However, the absolute change in ET was small because the annual mean temperature did not change very much (Figure 5-26). Therefore, evapotranspiration may not change much, even if global warming occurs (assuming only temperature increases).

Evapotranspiration from slash pine uplands was more sensitive to changes in relative humidity or VPD than ET from cypress wetlands (Figure 5-27 and Table 5-9). Aerodynamic conductance in both ecosystems was not a restricting factor to ET because the sensitivity of ET to wind speed was very low (Figure 5-28).

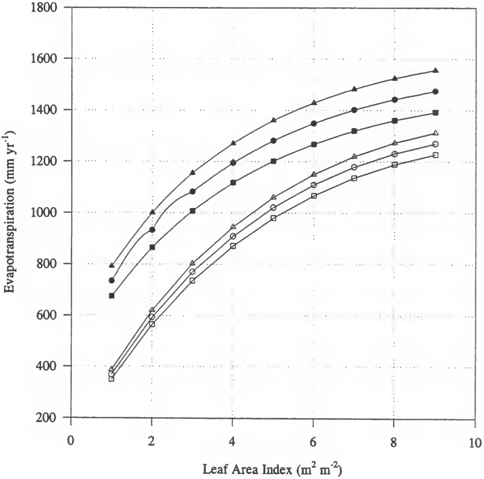


Figure 5-25. Relationships among evapotranspiration, leaf area index and solar radiation of cypress wetlands (closed) and pine uplands (open). Circles represents the situation of 1993. Triangles and squares represent the increase or reduction of solar radiation based on that of 1993.

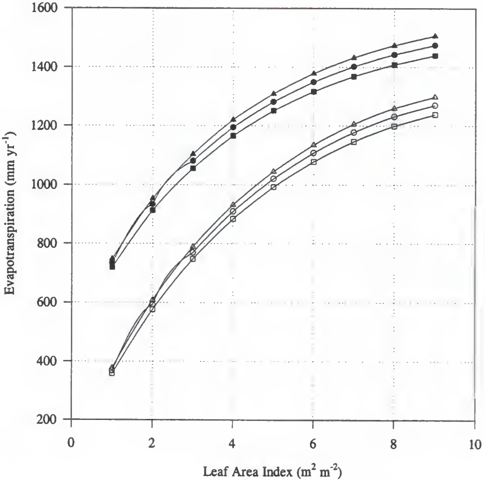


Figure 5-26. Effects of leaf area index and air temperature on the evapotranspiration of cypress wetlands (closed) and slash pine uplands (open). Circles represents the situation of 1993. Triangles and squares represent the situations after the air temperature increased or decreased by 1 °C based on 1993.

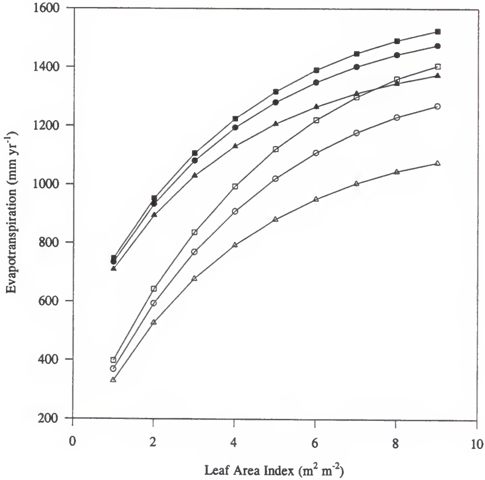


Figure 5-27. Effects of leaf area index and relative humidity of the air on the evapotranspiration of cypress wetlands (closed) and slash pine uplands (open). Circles represent the situation of 1993. Triangles and squares represent the situations after the relative humidity increased or decreased 10 percent based on 1993.

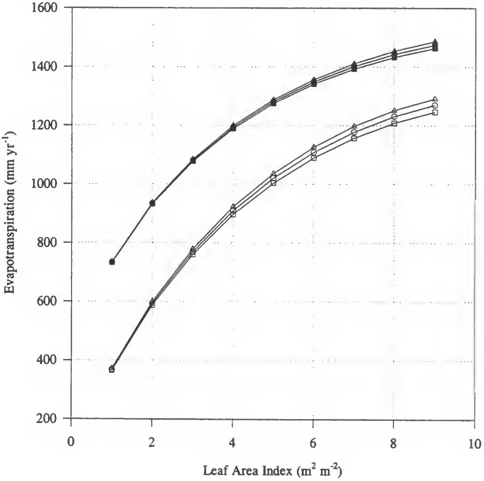


Figure 5-28. Effects of leaf area index and wind speed on the evapotranspiration of cypress wetlands (closed) and slash pine uplands (open). Circles represent the situation of 1993. Triangles and squares represent the situations after the wind speed is increased or decreased by 20 percent on the basis of 1993.

Table 5-9. Sensitivity analysis on the evapotranspiration model ETM.

Variable	Item	Cypress Wetlands			Pine Uplands		
		Base	+	-	Base	+	-
LAI	Value (m^2 m^{-2})	6	7	5	6	7	5
	ET (mm yr^{-1})	1349	1402	1281	1109	1178	1020
	Sensitivity[1]		24	30		37	48
Radiation (R)	Value (cal s^{-1} m^{-2})	68.7	75.1	61.9	68.7	75.1	61.9
	ET (mm yr^{-1})	1349	1429	1267	1109	1150	1067
	Sensitivity[1]		64	61		40	38
Temperature (Ta)	Value (^{0}C)	23.0	24.0	22.0	23.0	24.0	22.0
	ET (mm yr^{-1})	1349	1378	1316	1109	1135	1078
	Sensitivity[1]		49	56		54	64
VPD	Value (mbar)	10.6	12.6	8.6	10.6	12.6	8.6
	ET (mm yr^{-1})	1349	1391	1266	1109	1221	951
	Sensitivity[1]		17	33		54	76
Wind Speed	Value (m s^{-1})	2.3	2.7	1.8	2.3	2.7	1.8
	ET (mm yr^{-1})	1349	1357	1342	1109	1126	1090
	Sensitivity[1]		3	2		9	8
R, Ta and VPD	ET (mm yr^{-1})	1349	1501	1156	1109	1290	885
	Sensitivity[2]		102	130		148	184

[1] Sensitivity was calculated as: Sensitivity = [(ET change)/ET$_{base}$]/[(value change)/value$_{base}$]*100.

[2] (value change)/value$_{base}$ was considered as the average of the (value change)/value$_{base}$ for radiation, temperature and VPD.

Evapotranspiration from the ecosystems will increase or decrease significantly when radiation, air temperature and VPD increase or decrease simultaneously (Figure 5-29 and Table 5-9). Evapotranspiration from uplands tended to be more sensitive to this kind of change.

Maximum Evapotranspiration of the Ecosystems

Evapotranspiration from three cypress wetlands and their adjacent slash pine uplands has been estimated for the study sites. However, the estimated ET could not be used to answer questions such as what would be the maximum ET from both ecosystems in this region, because the LAI at these six sites was lower than the maximum LAI. However, these estimates did show the maximum evaporation from water surfaces in these wetlands. The results of the sensitivity analysis of ET from both ecosystems showed an overall picture of ET varying with LAI and environmental variables. If the understory LAI were assumed to be 1 m^2 m^{-2} and added to a maximum canopy LAI of slash pine plantations of 6 m^2 m^{-2} (Gholz, 1986), the ET from slash pine plantations would be around 1200 mm yr^{-1} (Figure 5-25). This value may represent the maximum ET from slash pine uplands in this region. In wetlands, the maximum LAI was about 7.5 m^2 m^{-2} (see Chapter 4). Therefore the maximum ET from cypress wetlands could be as high as 1400 mm yr^{-1}, which would be higher than the average annual rainfall of 1330 mm. The maximum ET from both ecosystems was close to the potential ET of about 1250 mm yr^{-1} in this area (Smajstrla et al., 1984). According to the analysis of LAI in Chapter 4, the regional average LAI in cypress wetlands was about 5.5 m^2 m^{-2} . This LAI produced an annual ET value of about 1080 mm yr^{-1}, which was about 80 percent of annual rainfall.

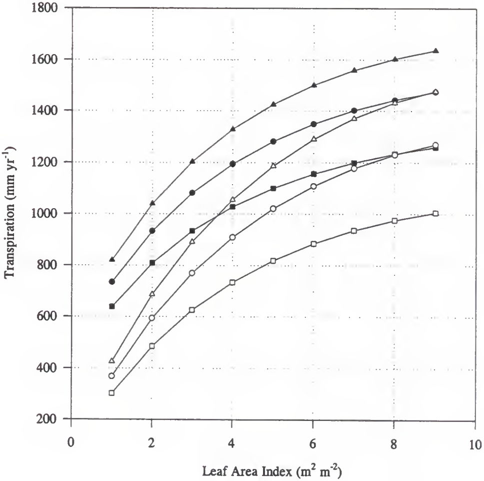


Figure 5-29. Effects of solar radiation, air temperature and relative humidity on the transpiration from cypress wetlands (closed) and slash pine uplands (open). Circles represent the situation of 1993. Triangles (sqaures) represent the situation after solar radiation increased (decreased) by 10 percent, air temperature increased (decreased) by 1 ^{0}C and relative humidity decreased (increased) by 10 percent on the basis of 1993.

CHAPTER 6
SUMMARY AND SUGGESTIONS

Originality of This Research

A new evapotranspiration model ETM, including three submodels of transpiration, rainfall interception and substrate evaporation, was developed and tested in this study.

A new submodel for the prediction of rainfall interception was theoretically derived. There were no empirical parameters in this submodel. Many interception models turned out to be special cases of the new model. Verification of the interception submodel with field measurements in three pairs of cypress wetlands and slash pine uplands, and with information from the literature showed very good results. Predictions by the new submodel was at least as accurate as the Gash and Mulder models. Further more, the interception submodel can be run on a hourly basis or event/daily basis.

Stomatal conductance of cypress and slash pine was measured at the leaf/needle level and modeled using readily available meteorological information such as PAR, VPD and air temperature. Results showed that multiple variable nonlinear models fitted the data statistically better than linear models. A 'Jarvis' model, based on the non-synergistic influences of multiple controlling factors on stomatal conductance, was compared to two models which assumed that only one or two strongest factors control stomatal conductance at any given time. All nonlinear models developed could be used to scale stomatal conductance up to the stand or landscape scales.

Transpiration was scaled from the leaf level up to the ecosystem level by incorporating information on ecosystem structure (e.g., species composition, tree density, DBH, height and LAI), turbulence transport in and from the canopy, stomatal conductance and other meteorological information. For the first time, the general combination equation (Lhomme, 1988a; 1988b) was applied to a real situation and compared with the multi-layer Penman-Monteith equation. Results showed that these two equations were practically equivalent in the prediction of transpiration from both cypress wetlands and slash pine uplands, although the multi-layer Penman-Monteith equation did not consider the aerodynamic conductance between layers. The results suggested that the aerodynamic conductance between adjacent layers in the canopy was not a restricting factor for transpiration at the ecosystem level. The transpiration submodels were compared with independent data acquired with an eddy correlation method and showed very good agreement.

The degree of coupling between the canopy and the overlying atmosphere, and its seasonal pattern were appraised using stomatal, boundary-layer, aerodynamic and radiation conductances, and other information such as species composition and the dynamics of leaf area index. It was found that the daily pattern of the degree of canopy-atmosphere coupling was not significantly different between cypress wetlands and slash pine uplands. However, the relationship between the coupling factor and LAI in cypress wetlands was significantly different from that at slash pine uplands.

A method for the estimation of evapotranspiration from water level fluctuations in cypress wetlands was further developed.

The evapotranspiration model ETM developed in this research has no limitation on the number of species involved and no limitation on the number of layers for the specification of the canopy. Other canopy processes such as sensible heat, CO_2 and other trace gases exchanges between the canopy and the atmosphere can be easily incorporated in ETM. The ETM can also be interfaced with other hydrological models to facilitate the prediction of runoff, subsurface flow and impacts of forest management practices on hydrology at different scales.

This research is so far the most comprehensive study ever conducted on the evapotranspiration (transpiration, rainfall interception and evaporation from water or soil surface) of cypress wetlands and their surrounding slash pine uplands in the southeastern United States. Field measurements and simulation results indicated that:

1. There was no significant difference in terms of transpiration and stomatal conductance between cypress and slash pine at the leaf/needle level during the growing season. The result is important to correct the perception that cypress has xeromorphic characteristics that decrease transpiration rates.

2. There was no significant difference in terms of annual transpiration between cypress wetlands and slash pine uplands at the canopy level. Although cypress is a deciduous species, different from slash pine, cypress wetlands tend to have higher leaf area indices than slash pine uplands during the growing season.

3. The rainfall storage capacity of cypress wetlands was higher than that of slash

pine uplands because of the higher storage capacities of cypress branches and stems and higher leaf area indices in wetlands. However, rainfall interception in cypress wetlands was not significantly more than that in pine uplands.

4. The evaporation rate from the surface of the standing water in cypress wetlands was about 1/3 of the potential evaporation rate in the open. Evaporation from wetlands varied from about 50 mm (in dry years) to 450 mm (in wet years), which was significantly higher than the evaporation from the soil surface in uplands during normal and wet years.

5. In total, evapotranspiration of cypress wetlands was not significantly different from that of slash pine uplands. However, a difference could have been significant depending on the extent of standing water in wetlands throughout the year. During wet years, annual evapotranspiration from wetlands was higher than from pine uplands, but during dry years, the difference was not significant.

6. Both cypress wetlands and slash pine uplands were well coupled with the atmosphere. Therefore, transpiration of these two ecosystems was mainly controlled by radiation, vapor pressure deficit of the air and stomatal conductance.

7. The average annual evapotranspiration was about 1080 mm from both ecosystems in this region, based on the average LAI. The maximum annual ET from cypress wetlands and slash pine uplands was about 1400 and 1200 mm, respectively, based on the maximum LAI and meteorological conditions of 1993.

Suggestions for Future Research

It has been demonstrated that stomatal conductance was controlled by a number of environmental variables. Higher stomatal conductances often occurred in the early morning when the VPD was lower. Consequently, the corresponding transpiration would be lower. Stomatal closure has not been observed in this study. Therefore, it would be interesting to see if average stomatal conductances instead of stomatal conductance models could be used in the prediction of transpiration. The result might be able to simplify the input data sets to ETM and facilitate large-scale predictions.

The submodel for substrate evaporation was related to the potential evaporation rate by a coefficient which was determined from the field measurements obtained from the three cypress wetlands of this study and uplands by Brown (1978), and the fraction of the wetland area covered by standing water or water table depth in the upland. An initial effort was to relate substrate evaporation to canopy characteristics such as LAI. However, the seasonal pattern of the predicted evaporation did not match that of the measured evaporation. This might have been due to energy advection between uplands and wetlands, the relative small size of the wetlands, and the fixed location of the floating pans in the wetlands. More soil evaporation data should be collected in slash pine uplands with varying LAI.

Rainfall interception has been observed in different stands (e.g., Heimburg, 1978; Allen and Gholz, 1995). Significant errors may exist in these data sets because of the non-sharp-edge gauges (either plastic funnels or troughs made from PVC pipes) used for the measurement of throughfall. Splashing may occur in shallow troughs. Several measures of gauge area have been used to convert throughfall from volume to depth. These measures were inner area (Allen and Gholz, 1995), outer area, and the average of these two (used in this study). Using the inner area of the gauge may result in a larger value of throughfall, and therefore a lower value of interception. Any error resulting from the gauge area measurements goes directly to throughfall and interception. A thorough study to appraise the efficiency and conversion area of various gauges for throughfall measurement is necessary.

Estimation of ET from water table fluctuations is also another interesting facet which needs to be refined. Soil moisture content change should be related to not only water table depth, but also to rainfall and other factors such as barometric pressure. A recording TDR would increase the frequency of observation which could lead to a better understanding of the relationship between soil moisture content and water table depth, rainfall and other factors.

Interfacing ETM with other distributed hydrological models will enable users to assess the impacts of forest management practices at the landscape scale, such as harvesting and species shifts. The hydrological, biological and chemical interactions between cypress wetlands and slash pine uplands could be better understood and predicted.

APPENDIX I
QBASIC SCRIPTS OF ETM

```
DECLARE SUB lhomme (n0, year, jday, jh, d!, cm, penman, fick, tr, wetet, watet, so!, ta!, rh!, vpd,
wind!, par, iter, ht, n1, lai, bai, clai, n2, et11, et21, sys$, pet, r)
DECLARE SUB soilevap (plot$, wt, subet)
DECLARE SUB sunangle (year, day, hr, elev)
DECLARE SUB pondevap (plot$, day, wt, wate, subet)
DECLARE SUB ansum (n0, year, yr$, sys$, file3$, file4$)

CLS
COLOR 7, 1, 7
LOCATE 5, 15:
PRINT " $
===============================================
$"
LOCATE 6, 15:
PRINT " $                                   $"
LOCATE 7, 15:
PRINT " $    This program is developed by Shuguang Liu    $"
LOCATE 8, 15:
PRINT " $                                   $"
LOCATE 9, 15:
PRINT " $       University of Florida, Gainesville       $"
LOCATE 10, 15:
PRINT " $                                   $"
LOCATE 11, 15:
PRINT " $            All rights are reserved !           $"
LOCATE 12, 15:
PRINT " $                  1995.6                  $"
LOCATE 13, 15:
PRINT " $
===============================================
$"
LOCATE 16, 5:
INPUT "Press RETURN key to continue", zzz$
CLS


start00! = TIMER
iter = 1
n0 = 0
```

```
REM COLOR 4, 8
REM LOCATE 4, 7:
REM PRINT "It's running ....."
REM LOCATE 5, 10:
REM prINT "Time Used (seconds)     Finished (%) "
COLOR 7, 4:
LOCATE 3, 27:
PRINT "                      "
LOCATE 4, 27:
PRINT "   MODEL  * E T M E *   "
LOCATE 5, 27:
PRINT "                      "
COLOR 2, 7
LOCATE 9, 6:
PRINT "  . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . ."
FOR i = 9 TO 23
 LOCATE i, 6:
 PRINT " . "
 LOCATE i, 73:
 PRINT " . "
NEXT i
LOCATE 23, 6:
PRINT "  . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . ."


        COLOR 7, 8
        LOCATE 12, 10:
        PRINT "Julian Day "
        LOCATE 7, 50:
        PRINT "Plot-Years: "
          LOCATE 15, 20:
          PRINT "P-M Multilayer "
          LOCATE 16, 20:
          PRINT "Interception "
        LOCATE 10, 25:
        PRINT "Year"
        LOCATE 10, 37:
        PRINT "System:"
        LOCATE 7, 15:
        PRINT "Starting Time: "; TIME$
        LOCATE 8, 15:
        PRINT "Current Time:  "

        LOCATE 14, 20:
        PRINT "Tr.(S. Liu) (mm)"
        LOCATE 17, 20:
        PRINT "Substrate E.(mm)"
        COLOR 1, 7
        LOCATE 18, 20:
        PRINT "Total ET (mm)"
        LOCATE 19, 20:
```

```
        PRINT "Eq. ET (mm)  "
        COLOR 7, 8
        LOCATE 21, 20:
        PRINT "All-sided LAI"
       LOCATE 22, 20:
       PRINT "Coupling (12 a.m.):"
       LOCATE 12, 50:
       PRINT "Cum. Rainfall"



file0$ = "c:\model\results\year_sys.dat"

OPEN file0$ FOR INPUT AS #21

plotyr = 0
WHILE NOT EOF(21)
n0 = n0 + 1
INPUT #21, year, sys$
plotyr = plotyr + 1
LOCATE 7, 62:
PRINT USING " ### "; plotyr
length = LEN(sys$)
wetup$ = RIGHT$(sys$, 1)
plot$ = LEFT$(sys$, length - 1)

annual = 0
awet = 0
apet = 0
aint = 0
apm = 0
aawet = 0
arain = 0
rec = 0


n2 = -1

file11$ = "c:\model\results\" + sys$ + "canop.dat"

OPEN file11$ FOR INPUT AS #11
INPUT #11, ht, n1, lai, bai:        REM number of layers, total LAI & BAI
REM lai = 30
REM bai = .2 * lai
REM n1 = n1:        REM add the substrate layer (substrate not included)
REM ht = ht + .1:        REM assume the depth of the substrate layer is 0.1 m
REM INPUT "Year:____?", year
REM PRINT "LAI: ", lai

       LOCATE 21, 50:
       PRINT "Max LAI: "; lai
```

```
    COLOR 0, 3

    LOCATE 10, 30:
    PRINT USING "####"; year
    LOCATE 10, 45:
    PRINT sys$

IF year / 4 = INT(year / 4) THEN
n = 366
ELSE
n = 365
END IF

IF iter = 1 THEN
DIM d(n), mm(n), da(n), jday(n), jh(n), r(n), p(n), c(n), et(n), in(n)
ELSE
REDIM d(n), mm(n), da(n), jday(n), jh(n), r(n), p(n), c(n), et(n), in(n)
END IF
iter = 2

REM The following data are defaults of some model parameters
d0 = 1          'Initial canopy Dryness index
b0 = .5         'Free throughfall coefficient or canopy openness
cm = 2!           'Canopy storage capacity (mm)
change = 1
count = 1
repeat = 1


p = 0: REM accumulated rainfall of a continuous rainfall (mm)
c = 0: REM water storage in canopy
et = 0: REM accumulated evaporation during rainfall (mm)
pmax = 0: REM maximum event rainfall (mm)
imax = 0: REM maximum event interception (mm)

d = 1
r1 = 0: REM assume no rainfall within an hour before the starting time
d1 = 1: REM assume the canopy is completely dry
c1 = 0: REM another expression of the assumption of dry canopy
in1 = 0: REM no interception
rec = 0
meanr = 0: REM mean rainfall intensity (mm/hr)
k = 0: REM rainfall duration (hrs)
m = 0
dry = 0: REM continously dry hour counter

IF year > 100 THEN year = year - 100 * INT(year / 100)
yr$ = STR$(year)
yr$ = RIGHT$(yr$, 2)
REM INPUT " What's the name of the system ? (kp, Cu, ...) ", sys$
```

```
file1$ = "c:\weather\19" + yr$ + ".gnv"
file2$ = "c:\model\" + sys$ + "\" + yr$ + "event." + sys$
file3$ = "c:\model\" + sys$ + "\" + yr$ + "daytr." + sys$
file4$ = "c:\model\" + sys$ + "\" + yr$ + "montr." + sys$
file5$ = "c:\model\" + sys$ + "\" + yr$ + "gchr." + sys$: REM canopy conductance
file6$ = "c:\model\" + sys$ + "\" + yr$ + "gcday." + sys$: REM canopy conductance
file20$ = "c:\wt\19" + yr$ + "." + sys$
file30$ = "c:\model\" + sys$ + "\" + yr$ + "pondet." + sys$

OPEN file1$ FOR INPUT AS #1
OPEN file2$ FOR OUTPUT AS #2
OPEN file3$ FOR OUTPUT AS #3
OPEN file4$ FOR OUTPUT AS #4
OPEN file5$ FOR OUTPUT AS #5
OPEN file6$ FOR OUTPUT AS #6
ON ERROR GOTO 100
OPEN file20$ FOR INPUT AS #20
OPEN file30$ FOR OUTPUT AS #30


    PRINT #30, " Jday";
    PRINT #30, " std H  ";
    PRINT #30, " Cover  ";
    PRINT #30, " WaterET";
    PRINT #30, " PondET "



PRINT #2, " Dry-T";
PRINT #2, "  day  ";
PRINT #2, " durat ";
PRINT #2, " inten ";
PRINT #2, "  rain ";
PRINT #2, " Dry(B)";
PRINT #2, " Dry(E)";
PRINT #2, " stor  ";
PRINT #2, " evap  ";
PRINT #2, " intec "

PRINT #3, "Mon ";
PRINT #3, "day ";
PRINT #3, "  rain  ";
PRINT #3, "  rad   ";
PRINT #3, "  ta    ";
PRINT #3, "  vpd   ";
PRINT #3, "  wind  ";
PRINT #3, " P.ET ";
PRINT #3, " ETLiu";
PRINT #3, " ETPM ";
PRINT #3, " Liu's";
PRINT #3, " P-M's";
PRINT #3, " Fick'";
PRINT #3, " Water";
PRINT #3, " SubE ";
PRINT #3, " wete ";
PRINT #3, " int  ";
PRINT #3, " dry  ";
PRINT #3, " trt  ";
PRINT #3, " rait ";
PRINT #3, " lai  ";
PRINT #3, "  Cm  ";
PRINT #3, "  WT  "



PRINT #5, " jday ";
PRINT #5, " hour ";
PRINT #5, " Dry    ";
PRINT #5, "  PAR   ";
PRINT #5, "  RAD   ";
PRINT #5, "  VPD   ";
PRINT #5, "  Ta    ";
PRINT #5, "  lhomme    ";
PRINT #5, "  Penman-M    ";
PRINT #5, "   Fick's    ";
PRINT #5, "  water s.   ";
PRINT #5, "    gs      ";
PRINT #5, "  Aero. (ga) ";
PRINT #5, "  L. B.cond. ";
PRINT #5, "  Omega(Mul) ";
PRINT #5, "  Omega(One) ";
PRINT #5, "     LAI     "



PRINT #6, " jday ";
PRINT #6, "   lhomme(mm) ";
PRINT #6, "   Penman-M   ";
PRINT #6, "   Fick's(mm) ";
PRINT #6, " Total gs     ";
PRINT #6, " L. B. Cond.  ";
PRINT #6, " Aero.(ga)    ";
PRINT #6, " Omega(layer) ";
PRINT #6, " Omega(tot)   ";
PRINT #6, "    LAI       "
start! = TIMER
PRINT #4, "                    Monthly Sum of ET Simulation                    "
PRINT #4, "                    "
PRINT #4, "                      "; sys$; "    "; year
PRINT #4, "  "
PRINT #4, "canopy height "; ht; " m"
PRINT #4, "Number of layers used for simulation: "; nl
PRINT #4, "Maximum LAI: "; lai
PRINT #4, "BAI: "; bai:        REM number of layers, total LAI & BAI

ll = lai + bai
REM PRINT "lai:", ll
WHILE NOT EOF(1)
     IF i / n * 10 = (i * 10) \ n THEN
          finish! = TIMER
          REM LOCATE 6 + 10 * i / n, 15:
          REM PRINT USING "########"; (finish! - start!)
          REM LOCATE 6 + 10 * i / n, 38:
          REM PRINT 100 * i / n
          IF i \ n = 1 THEN INPUT "Press RETURN key to continue", ccc$
     END IF
     INPUT #1, day, hh, so, ta, rh, par, wind, rain
     IF day / 10 = INT(day / 10) THEN
     LOCATE 8, 30:
     PRINT TIME$
     END IF

     rec = rec + 1

     REM IF rec = 1 OR rec / 1000 = INT(rec / 1000) THEN
     REM   LOCATE 8, 50:
     REM   PRINT day, hh
     REM END IF

     IF so < 0 THEN so = 0
     IF (20 < hh OR hh < 5) THEN so = 0
     REM PRINT "day, hh, d, so, lso, ta, par"
     REM PRINT so
     so = (1 - .12) * .238 * so * 1000000 / 3600: REM convert mj/m2 to cal/s/m2
     REM 0.12 is albedo
     wind = wind * 1000 / 3600:    REM  km/hr to m/s
     REM r = rain * 25: REM for interception calibration
     r = rain * 10:          REM cm to mm
     IF day < 32 THEN
      mmm = 1
     ELSEIF 31 < day AND day < 60 THEN
      mmm = 2
     ELSEIF 59 < day AND day < 91 THEN
      mmm = 3
     ELSEIF 90 < day AND day < 121 THEN
      mmm = 4
     ELSEIF 120 < day AND day < 152 THEN
      mmm = 5
     ELSEIF 151 < day AND day < 182 THEN
      mmm = 6
     ELSEIF 181 < day AND day < 213 THEN
      mmm = 7
     ELSEIF 212 < day AND day < 243 THEN
```

```
        mmm = 8
      ELSEIF 242 < day AND day < 273 THEN
        mmm = 9
      ELSEIF 272 < day AND day < 304 THEN
        mmm = 10
      ELSEIF 303 < day AND day < 334 THEN
        mmm = 11
      ELSEIF 333 < day AND day <= 365 THEN
        mmm = 12
      END IF

      IF rec = 1 THEN
      mon1 = mmm
      oneday3 = day
      REM ss$ = SYS$
      REM yy$ = yr$
      END IF

      tr = 0
      wet = 0

      REM CALL liu(day, hh, d1!, tr, wet, so, ta, rh, vpd, wind, par, iter, ht, n1, lai, bai, clai, n2, r)
      REM IF so > 0 OR d1 < 1 THEN
      CALL lhomme(n0, year, day, hh, d1!, cm, pm, fick, tr, wet, watet, so, ta, rh, vpd, wind, par,
  iter, ht, n1, lai, bai, clai, n2, et11, et21, sys$, pet, r)
      REM INPUT " ", a
      REM END IF
      REM PRINT d1, c1


      b0 = EXP(-(clai + bai) / 3)

      IF r > 0 THEN tr = 0
REM        PRINT "cm", cm

      IF r > 0 THEN
        det = 0
        k00 = k00 + 1: REM rainfall duration counter
        REM determine the canopy dryness index before rainfall
        IF (r1 = 0) THEN
            d = d1
        END IF

        REM LOCATE 7, 10:
        REM PRINT "d1, dd, d";
        REM PRINT USING "##.### "; d1; dd; d
        REM INPUT "  ", ss$


        REM PRINT "d1, d R ,HH, WET  ";
        REM PRINT USING "##.##  "; d1; d; R; hh; wet
  dc = cm * dd: REM temperal change of canopy storage
  c = c1 + dc: REM canopy storage at time jh(i)

  ew = wet
  REM CALL wetevap(ew, c, so, ta, rh, wind, ll, ht)
  REM print d1, d
  REM lhomme's equation gives the total flux from the canopy
  de = ew * (1 - (d1 + d) / 2)
  maxde = r * (1 - b0) - dc
  IF de > maxde THEN de = maxde
  IF r1 = 0 THEN de = de / 2
  REM de = ew * ll + ew * ll * d1 * (1 - b0) * r * Inst / cm - ew * ll * d1 * Inst
          REM whole canopy evaporation rate at time jh(i)
  REM PRINT "wet:", de
  et = et1 + de: REM accumulated evaporation at time jh(i)
  REM T et1, de, et
  REM PRINT "r, de, et, in ";
  REM PRINT USING "###.##  "; r; de; et; in
  REM IF in > imax THEN imax = in: REM find max interception
  p = p1 + r: REM accumulated rainfall at time jh(i)
  REM IF p > pmax THEN pmax = p: REM find max rainfall
  count = 1: REM controller of data output
  IF count2 = 1 THEN PRINT #2, USING "######"; dry;
  dry = 0
  meanr = p / k00: REM mean rainfall intensity during an event
  count2 = 0
END IF

IF r > 0 AND dd < .05 THEN
wettt = wettt + wet
rhr = rhr + 1
meanw = wettt / rhr
LOCATE 2, 10:
PRINT USING "####  "; rhr;
PRINT USING "#####.##  "; meanw;
IF wet > wetetm THEN
wetetm = wet
PRINT USING "#####.##  "; wetetm; vpd; rh; ta
END IF
END IF

REM calculate wet canopy evaporation when no rainfall
IF (r = 0 AND c1 > 0) THEN
    IF r1 > 0 AND k00 > 1 THEN
    et1 = et1 - de / 2
    in1 = in1 - de / 2
    END IF
    dry = dry + 1: REM continuously dry hours
      REM output the event-based data
      REM duration and amount of rainfall (k and p)
      REM dryness index, storage, total evaporation and interception at the end of rainfall
    IF count = 1 THEN
    REM PRINT "day, p1, int", day, p1, in1
    PRINT #2, USING "#######"; day; k00;
    PRINT #2, USING "####.##"; meanr; p1; d; d1; c1; et1; in1
    REM PRINT USING "#######"; day; k00;
    REM PRINT USING "####.##"; meanr; p1; d; d1; c1; et1; in1
    END IF
    k00 = 0: REM rezero the next rainfall duration
    count = 2: REM controller of the output
    in = 0: REM rezero next interception
    p = 0: REM rezero next rainfall
    et = 0: REM rezero total evaporation of next rainfall

    REM ed is the unit area rate while wet is the whole canopy rate

    ed = wet * (1 - d1)

    d = 1 - (1 - d1) * EXP(-ed / cm)

    dc = (d - d1) * cm

    REM IF c1 > 0 THEN CALL wetevap(ed, c1, so, ta, rh, wind, ll, ht)
    REM PRINT "wet, ed:   ", wet, ed
    dd = d - d1: REM temperal change of dryness after rainfall stoped
    REM d = d1 + dd: REM canopy dryness at time jh(i) (no rainfall)
    REM PRINT "dry: d1, d, dd ";
    REM PRINT USING "##.## "; d1; d; dd
    c = (1 - d) * cm


    REM LOCATE 23, 5:
    REM PRINT "c1, d1, dd, c";
    REM PRINT USING " #.### "; c1; d1; dd; c

    REM IF c1 > 0 THEN PRINT "dryet, before, ed, after, dry"; USING "##.###"; det; c1; ed; c; d

  REM the following is transpiration calculation

  REM PRINT "sys:", sys$
  REM PRINT day, hh, d, so, ta
  REM INPUT " ", s$
  REM IF r = 0 THEN CALL lhomme(day, hh, d, so, ta, rh, wind, par, iter, ht, n1, lai, bai, n2)
  REM PRINT day, hh, d, so, ta
  jh = hh + day * 24
  count2 = 1
  END IF
  REM IF d > 1 THEN INPUT "  ", bbs

IF vpd > maxvpd THEN
maxvpd = vpd
END IF
IF so > som THEN
som = so
END IF
IF ta > tmax THEN
tmax = ta
END IF
IF wind > windm THEN
windm = wind
END IF
REM tr based on regression equation
IF r = 0 AND so > .5 THEN
  trt = trt + 1:    REM daily transpiration time (hr)
  gstr = .0373 * vpd * 18 * 3600 / 1000000 * clai
END IF

  daytr = daytr + tr:    REM daily transpiration (mm)
  daypet = daypet + pet
  daywatet = daywatet + watet
  daygstr = daygstr + gstr

IF so > .5 THEN
   tta = tta + ta
   tso = tso + so
   tvpd = tvpd + vpd
   td = td + d1
   twind = twind + wind
   dlenth = dlenth + 1
END IF

IF r > 0 THEN
   raint = raint + 1: REM rain time (hrs)
   wete = wete + de:  REM evaporation during rainfall
   stor = stor + dc:   REM Interception storage
   drain = r + drain:   REM total daily rainfall
ELSE
   drye = drye + (d - d1) * cm:   REM wet canopy evaporation during dry period
END IF


IF day < oneday3 OR day > oneday3 THEN

numb = numb + 1:  REM number of days in a month included

  annual = annual + daytr
  awet = awet + daywatet: REM potential water evapo
  apm = apm + pm
  apet = apet + daypet
  arain = arain + drain: REM cumulative rainfall
  aint = aint + stor + wete:  REM cumulative interception
  ann = ann + daygstr
   IF dlenth > 0 THEN
   dta = tta / dlenth:      REM calculate mean daily values
   dso = tso / dlenth
   dvpd = tvpd / dlenth
   dwind = twind / dlenth
   ddd = td / dlenth:          REM mean dryness index
   END IF
   REM CLS

 loca1 = LOC(20)


 IF NOT EOF(20) THEN
 INPUT #20, yy, jday, wt
 END IF
 IF day < jday THEN
     SEEK (20), loca1
 END IF

WHILE jday < day AND (NOT EOF(20))
 INPUT #20, yy, jday, wt
WEND

IF (jday = day) AND (wetup$ = "p" OR wetup$ = "P") THEN
  CALL pondevap(plot$, day, wt, daywatet, ratio)
END IF

IF (jday = day) AND (wetup$ = "u" OR wetup$ = "U") THEN
  CALL soilevap(plot$, wt, ratio)
  REM LOCATE 4, 50:
  REM PRINT USING " ###.## "; ratio
END IF
  REM LOCATE 5, 40:
  REM PRINT USING " ####.## "; day; wt; ratio

REM IF drain > 5 THEN
REM IF INT(dry / 24) = 0 THEN
REM ratio2 = 1
REM ELSE
REM ratio2 = .5 / (dry / 24) ^ (.5)
REM END IF
REM END IF

REM IF wetup$ = "u" OR wetup$ = "U" THEN
REM    IF ratio2 > ratio THEN ratio = ratio2
REM END IF
```

```
subet = ratio * daywatet

 aawet = aawet + subet: REM annual evapo from substrate


 REM output daily data

 dayet1 = daytr + subet + wete + stor
 dayet2 = pm + subet + wete + stor
 PRINT #3, USING "####"; mmm; day;
 PRINT #3, USING "#####.##"; drain; dso; dta; dvpd; dwind; daypet; dayet1; dayet2;
 PRINT #3, USING "###.##"; daytr; pm; fick; daywatet; subet; wete; wete + stor; ddd;
 PRINT #3, USING "######"; trt; raint;
 PRINT #3, USING "###.##"; clai; cm; wt

 LOCATE 12, 22:
 PRINT USING "####"; day;
 LOCATE 14, 40:
 PRINT USING " ####.## "; annual;
 LOCATE 14, 55:
 PRINT USING "   ##.## "; daytr
 LOCATE 16, 40:
 PRINT USING " ####.## "; aint
 LOCATE 17, 40:
 PRINT USING " ####.## "; aawet
 LOCATE 18, 40:
 PRINT USING " ####.## "; annual + aint + aawet
 LOCATE 18, 55:
 PRINT USING " ####.## "; apm + aint + aawet
 LOCATE 21, 40:
 PRINT USING "   ##.## "; clai
 LOCATE 12, 65:
 PRINT USING "####.##"; arain
  LOCATE 19, 40:
  PRINT USING " ####.## "; apet

  tta = 0
  tso = 0
  tvpd = 0
  td = 0
  twind = 0
  dlenth = 0

  drain = 0
  dta = 0
  dso = 0
  dvpd = 0
  dwind = 0
  ddd = 0

daytr = 0
```

```
       daywatet = 0
       daypet = 0
       daygstr = 0
       wete = 0
       drye = 0
       stor = 0
       trt = 0
       raint = 0
       maxt = 0
       parm = 0
       tmax = -30

       windm = 0
       oneday3 = day
       END IF

      d1 = d
      r1 = r
      c1 = c
      et1 = et
      in1 = in
      p1 = p
      REM LOCATE 8, 10:
      REM PRINT "d1, c1, wet";
      REM PRINT USING "##.### "; d1; c1; wet
WEND
CLOSE #1, #2, #3, #4, #5, #6, #11, #20, #30

CALL ansum(n0, year, yr$, sys$, file3$, file4$)

WEND
CLOSE #21
STOP


100 : IF ERR = 53 THEN OPEN "C:\wt\1993." + sys$ FOR INPUT AS #20
  RESUME NEXT




WHILE a$ = "0"
CLS
SCREEN 0
PRINT "  "
INPUT "Do you want to plot the results ? (Y/N) "; aa$
WHILE aa$ = "y" OR aa$ = "Y"
PRINT "The data available is from "; jh(1); " to "; jh(n); " hours of the year."
INPUT "Do you want to plot all the data? (Y/N)"; a$
IF a$ = "n" OR a$ = "N" THEN
      INPUT "What is the beginning hour for plotting"; bhour
      INPUT "What is the ending hour for plotting"; ehour
      lowx = bhour
      highx = ehour
      add = (ehour - bhour) * .05: REM position ajustor
ELSE
      lowx = jh(1)
      add = INT((jh(n) - jh(1)) * .05): REM position ajustor
      highx = jh(n)
END IF

INPUT "Do you want to show rainfall and interception in one plot (y/n)"; plot$
IF plot$ = "n" OR plot$ = "N" THEN
      viewmax = 60
      tick = 1
ELSE
      viewmax = 120
      tick = 2
END IF

CLS 0
SCREEN 8
jh(0) = jh(1) - 1
LOCATE 1, 1: PRINT "Plots shown:"

WINDOW (lowx - add, -5)-(highx + add, pmax + 5)
LOCATE 5, 3: PRINT USING "##.#"; INT(pmax / 10 + 1) * 10
IF viewmax = 60 THEN
   LOCATE 7, 3: PRINT USING "##.#"; 0!
ELSE
   LOCATE 13, 3: PRINT USING "##.#"; 0!
END IF
IF viewmax = 120 THEN
   LOCATE 2, 15: PRINT "Event Cumulative Rainfall and interception (mm)"
ELSE
   LOCATE 2, 20
   PRINT "Event Cumulative Rainfall (mm)"
END IF
SCREEN 8
VIEW (50, 20)-(600, viewmax), 1, 3
FOR i = 1 TO 10
   LINE (jh(0) - add, (i - 1) * 5)-(jh(0) - add + add / 5, (i - 1) * 5)
NEXT i
FOR i = 1 TO n
   IF lowx <= jh(i) AND jh(i) <= highx THEN
         LINE (jh(i), 0)-(jh(i), r(i)), 14
      IF viewmax = 120 AND in(i) > in(i - 1) THEN
         LINE (jh(i), 0)-(jh(i), in(i) - in(i - 1)), 12
      END IF
      IF da(i) > da(i - 1) OR da(i) < da(i - 1) THEN
            LINE (jh(i), 0)-(jh(i), -.05 * pmax / tick)
         IF mm(i) > mm(i - 1) OR mm(i) < mm(i - 1) THEN
```

```
               LINE (jh(i), 0)-(jh(i), -.15 * pmax / tick), 15
            END IF
         END IF
      END IF
      IF i = 1 THEN
         LOCATE 1, mm(1) - mm(0) + 16: PRINT mm(i); "/"; da(i); " to ";
      END IF
      IF i = n THEN
         LOCATE 1, mm(n) + 20: PRINT mm(i); "/"; da(i); "."
      END IF
NEXT i
LINE (lowx, 0)-(highx, 0), 15

IF viewmax = 60 THEN
   WINDOW (lowx - add, -1)-(highx + add, imax + 1)
   LOCATE 11, 3: PRINT USING "##.#"; INT(imax + 1)
   LOCATE 14, 3: PRINT USING "##.#"; 0!
   LOCATE 10, 30: PRINT "Interception (mm)"
   VIEW (50, 80)-(600, 120), 1, 3
   FOR i = 1 TO 10
     LINE (jh(0) - add, (i - 1))-(jh(0) - add + add / 5, (i - 1))
   NEXT i
    FOR i = 1 TO n
       IF lowx < = jh(i) AND jh(i) < = highx AND in(i) > in(i - 1) THEN
          LINE (jh(i), 0)-(jh(i), in(i) - in(i - 1)), 13
       END IF
          IF da(i) > da(i - 1) OR da(i) < da(i - 1) THEN
             LINE (jh(i), 0)-(jh(i), -.05 * imax)
             IF mm(i) < mm(i - 1) OR mm(i) > mm(i - 1) THEN
                 LINE (jh(i), 0)-(jh(i), -.2 * imax), 15
             END IF
          END IF
        LINE (lowx, 0)-(highx, 0), 15
      NEXT
END IF

WINDOW (lowx - add, -.5)-(highx + add, 1.5)
LOCATE 19, 3: PRINT USING "##.#"; 1!
LOCATE 22, 3: PRINT USING "##.#"; 0!
LOCATE 17, 30: PRINT "Wetness Index"
VIEW (50, 140)-(600, 180), 1, 3
FOR i = 1 TO 3
   LINE (jh(0) - add, (i - 1) * .5)-(jh(0) - add + add / 5, (i - 1) * .5)
NEXT i
LINE (lowx, 0)-(highx, 0), 15
FOR i = 1 TO n
   IF lowz < = jh(i) AND jh(i) < = highx THEN
         LINE (jh(i - 1), 1 - d(i - 1))-(jh(i), 1 - d(i)), 12
      IF da(i) > da(i - 1) OR da(i) < da(i - 1) THEN
             LINE (jh(i), 0)-(jh(i), -.05)
          IF mm(i) > mm(i - 1) OR mm(i) < mm(i - 1) THEN
```

```
                LINE (jh(i), 0)-(jh(i), -.2), 15
            END IF
        END IF
    END IF
NEXT

LOCATE 24, 3: INPUT "Do you want to re-plot the results ? (Y/N) "; aa$
CLS 0
WEND
SCREEN 0
CLS
LOCATE 6, 1:
PRINT "Facts: 1) This trial took "; FIX((TIMER - start0!) / 6) / 10; " minutes to finish. "
PRINT "       2) The program has been running for "; FIX((TIMER - start00!) / 6) / 10; " minutes."
LOCATE 10, 20:
PRINT " 0 -- Quit "
LOCATE 12, 20:
PRINT " 1 -- Another Trial  "
LOCATE 14, 15:
INPUT "Selection: ", repeat
IF repeat < > 0 THEN change = 31
IF repeat = 0 THEN STOP
CLOSE #1, #2, #3, #4, #11
CLS
WEND

SUB ansum (n0, year, yr$, sys$, file3$, file4$)

      OPEN file3$ FOR INPUT AS #1

      OPEN file4$ FOR APPEND AS #3
PRINT #3, "  "
PRINT #3, " mon";
PRINT #3, " Day";
PRINT #3, "  rain ";
PRINT #3, "  rad. ";
PRINT #3, "  Ta.  ";
PRINT #3, "  VPD  ";
PRINT #3, "  wind ";
PRINT #3, " Pot. ET";
PRINT #3, " ET(Liu)";
PRINT #3, " ET(PM) ";
PRINT #3, "  Liu's";
PRINT #3, "  P-M's";
PRINT #3, "  Fick ";
PRINT #3, "  Water";
PRINT #3, "  Substr";
PRINT #3, "  wete ";
PRINT #3, "  int. ";
PRINT #3, "  drye.";
PRINT #3, "  dryne";
PRINT #3, "   LAI  ";
PRINT #3, "   WT(m)"


     IF n0 = 1 THEN
     OPEN "c:\model\total.res" FOR OUTPUT AS #2

PRINT #2, " Yr ";
PRINT #2, " Sys";
PRINT #2, " Day";
PRINT #2, "   rain ";
PRINT #2, "   rad. ";
PRINT #2, "   Ta.  ";
PRINT #2, "   VPD  ";
PRINT #2, "   wind ";
PRINT #2, " Pot.ET ";
PRINT #2, " ET(liu)";
PRINT #2, " ET(PM) ";
PRINT #2, "   Liu's";
PRINT #2, "   P-M's";
PRINT #2, "   Fick ";
PRINT #2, "   Water";
PRINT #2, " Substr ";
PRINT #2, "   wete ";
PRINT #2, "   int. ";
PRINT #2, "   drye.";
PRINT #2, "   dryne";
PRINT #2, "   LAI  ";
PRINT #2, "   WT(m)"

      ELSE
     OPEN "c:\model\total.res" FOR APPEND AS #2
     END IF
      numb = 0
      no = 0
      LINE INPUT #1, title$

      WHILE NOT EOF(1)

      REM PRINT title$
      REM INPUT "  ", b


      INPUT #1, mmm1

      no = no + 1

      IF no = 1 THEN mm = mmm1

      IF mmm1 < mm OR mmm1 > mm THEN
```

```
    totnum = totnum + numb
    monso = monso / numb
    monta = monta / numb
    monvpd = monvpd / numb
    monwind = monwind / numb
    mond = mond / numb
    monclai = monclai / numb
    monwt = monwt / numb

    con = 30 / numb
    monpet = monpet * con
    monet1 = monet1 * con
    monet2 = monet2 * con
    monlius = monlius * con
    montr = montr * con
    monwet = monwet * con
    monwate = monwate * con
    monwete = monwete * con
    monstor = monstor * con
    monint = monint * con

    PRINT #3, USING "####"; mmm1 - 1; numb;
    PRINT #3, USING " ####.##"; monrain; monso; monta; monvpd; monwind; monpet; monet1;
monet2;
    PRINT #3, USING " ####.##"; monlius; montr; monwet; monwate; monwete;
    PRINT #3, USING " ###.##"; monstor; monint; mondrye; mond; monclai; monwt

    REM annual sum
    monno = monno + 1
    anumb = anumb + numb
    amonrain = amonrain + monrain
    amonso = amonso + monso
    amonta = amonta + monta
    amonvpd = amonvpd + monvpd
    amonwind = amonwind + monwind
    amonpet = amonpet + monpet
    amonet1 = amonet1 + monet1
    amonet2 = amonet2 + monet2
    amonlius = amonlius + monlius
    amontr = amontr + montr
    amonwet = amonwet + monwet
    amonwate = amonwate + monwate
    amonwete = amonwete + monwete
    amonstor = amonstor + monstor
    amonint = amonint + monint
    amond = amond + mond
    amonclai = amonclai + monclai
    amonwt = amonwt + monwt

    mm = mmm1
    numb = 0
```

```
monrain = 0
monso = 0
monta = 0
monvpd = 0
monwind = 0
monpet = 0
monet1 = 0
monet2 = 0
monlius = 0
montr = 0
monwet = 0
monwate = 0
monwete = 0
monstor = 0
monint = 0
mond = 0
monclai = 0
monwt = 0

END IF

INPUT #1, numb1, monrain1, monso1, monta1, monvpd1, monwind1, pet, et1, et2
INPUT #1, lius, montr1, monwet1, monwate1, monwete1, monstor1, monint1
INPUT #1, mond1, trt, train, monclai1, cm, wt


numb = numb + 1
monrain = monrain + monrain1
monso = monso + monso1
monta = monta + monta1
monvpd = monvpd + monvpd1
monwind = monwind + monwind1
monpet = monpet + pet
monet1 = monet1 + et1
monet2 = monet2 + et2
monlius = monlius + lius
montr = montr + montr1
monwet = monwet + monwet1
monwate = monwate + monwate1
monwete = monwete + monwete1
monstor = monstor + monstor1
monint = monint + monint1
mond = mond + mond1
monclai = monclai + monclai1
monwt = monwt + wt


WEND

totnum = totnum + numb
monso = monso / numb
```

```
      monta = monta / numb
      monvpd = monvpd / numb
      monwind = monwind / numb
      mond = mond / numb
      monclai = monclai / numb
      monwt = monwt / numb

      con = 30 / numb
      monpet = monpet * con
      monet1 = monet1 * con
      monet2 = monet2 * con
      monlius = monlius * con
      montr = montr * con
      monwet = monwet * con
      monwate = monwate * con
      monwete = monwete * con
      monstor = monstor * con
      monint = monint * con

      PRINT #3, USING "####"; mmm1; numb;
      PRINT #3, USING " ####.##"; monrain; monso; monta; monvpd; monwind; monpet; monet1;
monet2;
      PRINT #3, USING " ####.##"; monlius; montr; monwet; monwate; monwete; monstor;
      PRINT #3, USING " ###.##"; monint; mondrye; mond; monclai; monwt


      REM annual sum
      monno = monno + 1
      anumb = anumb + numb
      amonrain = amonrain + monrain
      amonso = amonso + monso
      amonta = amonta + monta
      amonvpd = amonvpd + monvpd
      amonwind = amonwind + monwind
      amonpet = amonpet + monpet
      amonet1 = amonet1 + monet1
      amonet2 = amonet2 + monet2
      amonlius = amonlius + monlius
      amontr = amontr + montr
      amonwet = amonwet + monwet
      amonwate = amonwate + monwate
      amonwete = amonwete + monwete
      amonstor = amonstor + monstor
      amonint = amonint + monint
      amond = amond + mond
      amonclai = amonclai + monclai
      amonwt = amonwt + monwt

      amonso = amonso / monno
      amonta = amonta / monno
      amonvpd = amonvpd / monno
```

```
        amonwind = amonwind / monno
        amond = amond / monno
        amonclai = amonclai / monno
        amonwt = amonwt / monno


        PRINT #2, USING "####"; year;
        PRINT #2, " "; sys$;
        PRINT #2, USING "####"; anumb;
        PRINT #2, USING " ####.##"; amonrain; amonso; amonta; amonvpd; amonwind; amonpet;
amonet1; amonet2;
        PRINT #2, USING " ####.##"; amonlius; amontr; amonwet; amonwate; amonwete; amonstor;
amonint; amondrye; amond;
        PRINT #2, USING " ###.##"; amonclai; amonwt

       PRINT #3, "--------Annual Sum---------"
        PRINT #3, USING "####"; year; anumb;
        PRINT #3, USING " ####.##"; amonrain; amonso; amonta; amonvpd; amonwind; amonpet;
amonet1; amonet2;
        PRINT #3, USING " ####.##"; amonlius; amontr; amonwet; amonwate; amonwete; amonstor;
amonint; amondrye; amond;
        PRINT #3, USING " ###.##"; amonclai; amonwt


       CLOSE #1, #2, #3

END SUB

SUB lhomme (n0, year, jday, jh, d!, cm, penman, flux1, tet, wetet, watet, so!, ta!, rh!, vpd, wind!, par,
iter, ht, n1, lai, bai, clai, n2, et11, et21, sys$, pet, r) STATIC


       REM PRINT so, d
       IF par < 0 THEN par = 0
       REM IF so > mso THEN mso = so
       REM LOCATE 2, 40:
       REM PRINT mso
       REM INPUT " ", a
       par = 1000000 * par / 3600
       REM PRINT "par, so, jday, jh:", par, so, jday, jh
       REM read the canopy file once during the first loop
       gs = 0
       calib = 0
       REM so = .95 * so
       REM PRINT "n0", n0
       REM INPUT "  ", a
       REM shtso = so
       REM temp = ta + 273
       REM efac = .92 * temp * temp / 100000
       REM stephan = .00000001354#
       REM lso = (efac - 1) * .97 * stephan * temp ^ 4
REM so = .8 * (shtso + lso)
REM PRINT day, hh, d, shtso, lso, ta, par
REM INPUT " ", a
REM Brutsaert (1982) 218 p.
REM upl = .97 * stephan * temp ^ 4
REM downl = .97 * efac * stephan * temp ^ 4

IF n2 < > n1 THEN

  INPUT #11, spec:        REM number of species in ecosystem
  PRINT #4, "Number of species in the canopy: "; spec

  IF n0 = 1 THEN
  ss$ = sys$
  DIM species$(spec), wlai(spec), leafw(spec), clai(spec)
  DIM slai(spec, n1), par(n1 + 1)
  DIM vlai(n1), lays(n1), spl(n1)
  DIM lai(n1 + 1), bai(n1 + 1), sai(n1 + 1), ht(n1 + 1)
  DIM u(n1 + 1), k(n1 + 1), rb(n1 + 1), gb(n1 + 1), gs(n1 + 1)
  DIM ga(n1 + 1), gev(n1 + 1), gec(n1 + 1), rn(n1 + 1)
  DIM ac(n1 + 1), bw(n1 + 1), c(n1 + 1), cc(n1 + 1), cv(n1 + 1)
  DIM av(n1 + 1), b(n1 + 1), ev(n1 + 1), efv(n1 + 1, n1 + 1)
  DIM d(n1 + 1), ec(n1 + 1), efc(n1 + 1, n1 + 1), aw(n1 + 1), ccw(n1 + 1)
  DIM alphac(n1 + 1), beltac(n1 + 1)
  DIM alphav(n1 + 1), beltav(n1 + 1)
  DIM alphaw(n1 + 1), beltaw(n1 + 1)

  ELSE
  REDIM species$(spec), wlai(spec), leafw(spec), clai(spec)
  REDIM slai(spec, n1), par(n1 + 1)
  REDIM vlai(n1), lays(n1), spl(n1)
  REDIM lai(n1 + 1), bai(n1 + 1), sai(n1 + 1), ht(n1 + 1)
  REDIM u(n1 + 1), k(n1 + 1), rb(n1 + 1), gb(n1 + 1), gs(n1 + 1)
  REDIM ac(n1 + 1), bw(n1 + 1), c(n1 + 1), cc(n1 + 1), cv(n1 + 1)
  REDIM av(n1 + 1), b(n1 + 1), ev(n1 + 1), efv(n1 + 1, n1 + 1)
  REDIM d(n1 + 1), ec(n1 + 1), efc(n1 + 1, n1 + 1), aw(n1 + 1), ccw(n1 + 1)
  REDIM alphac(n1 + 1), beltac(n1 + 1)
  REDIM alphav(n1 + 1), beltav(n1 + 1)
  REDIM alphaw(n1 + 1), beltaw(n1 + 1)
  REDIM ga(n1 + 1), gev(n1 + 1), gec(n1 + 1), rn(n1 + 1)
  END IF

REM read canopy structure data

  ht(0) = ht
  u(0) = wind
  sai(0) = 0
  REM PRINT "lai, ht", lai, ht(0)

REM Canopy layers
  PRINT #4, "Height of each layer (m): ";
```

```
   FOR n = 1 TO nl
     INPUT #11, ht(n)
     IF n < nl THEN
     PRINT #4, ht(n);
     ELSE
     PRINT #4, ht(n)
     END IF
     REM  PRINT "h:", USING "###.#"; h(n);
   NEXT n

   REM LAI vertical distribution
   PRINT #4, "Vertical distri. of LAI : ";

   FOR n = 1 TO nl
     INPUT #11, vlai(n)
     IF n < nl THEN
     PRINT #4, vlai(n);
     ELSE
     PRINT #4, vlai(n)
     END IF
   NEXT n

   REM species, leaf width and weight of LAI (at max LAI) for each species

   PRINT #4, "Species Name     Leaf Width     LAI weight"
   FOR j = 1 TO spec
     INPUT #11, species$(j), leafw(j), wlai(j)
     PRINT #4, species$(j);
     PRINT #4, USING "  ####.###   "; leafw(j); wlai(j)
      REM PRINT "leafw, wlai(j):", leafw(j), wlai(j)
   FOR i = 1 TO nl
      REM presence of LAI of a specific species in a layer (1 or 0)
      INPUT #11, slai(j, i)
   NEXT i
   NEXT j


 FOR i = 1 TO spec
 INPUT #11, g0(i), gmax(i), b0(i), t0(i), a0(i), s1(i), s2(i)
 REM PRINT g0(i), gmax(i), b0(i), t0(i), a0(i), s1(i), s2(i)
 NEXT i


 REM determine the LAI weight of each species in each layer
 REM     when the leaves are fully expanded
 REM     at the middle at the growing season
   tst = 0
   tsst = 0
   FOR i = 1 TO spec
     ts(i) = 0
     tso(i) = 0
```

```
NEXT
FOR i = 1 TO nl
 ll1(i) = 0
NEXT


FOR j = 1 TO spec
FOR i = 1 TO nl:     REM  to calculate the weight of LAI of each species at layer i
   ts(j) = ts(j) + ssl1(j, i):   REM total LAI weight of a species (calcualted need to be corrected)
   REM PRINT species$(j), i, wlai(j), vlai(i), ssl1(j, i)
   tst = tst + ssl1(j, i): REM total weight of all species
NEXT i
REM PRINT
REM PRINT "lai weight, total weight", species$(j), ts(j), tst
NEXT j
REM PRINT tst
REM INPUT " ", a

FOR j = 1 TO spec
FOR i = 1 TO nl
   IF ll1(i) > 0 THEN
   REM PRINT USING " ##.### "; ssl1(j, i); ssl1(j, i) / ll1(i);
   ssl1(j, i) = vlai(i) * ssl1(j, i) / ll1(i)
   REM PRINT USING " ##.#### "; i; ssl1(j, i); vlai(i); ll1(i)
   END IF
NEXT i
   REM PRINT " "
NEXT j
REM PRINT tsst
REM INPUT " ", a

FOR j = 1 TO spec
FOR i = 1 TO nl
   ssl0(j, i) = ssl1(j, i) * wlai(j) / tso(j)
   REM PRINT wlai(j) / ts(j)
   REM PRINT "i, species, LAI weight", i, species$(j), ssl0(j, i)
   REM PRINT "total:", tottal
   REM INPUT "  ", a$
NEXT i
NEXT j
REM PRINT ts
REM INPUT " ", a


REM tottal = 0
REM FOR j = 1 TO spec:    REM calculate the weight of a species in layer i
REM     tw(j) = tst * wlai(j):   REM LAI weight of species i (input data)
REM     spe(j) = tw(j) / ts(j):   REM correction coefficient of LAI weight
REM     REM PRINT "species, leaf weight, coorect", species$(j), tw(j), spe(j)
REM FOR i = 1 TO nl
REM     ssl0(j, i) = ssl1(j, i) * spe(j) / tst: REM LAI weight of Species j at layer i
```

```
  REM     tottal = tottal + ssl0(j, i)
  REM NEXT
  REM NEXT
REM PRINT "total", tottal



 REM alpha(1) = 1:                REM Lhomme's
 REM belta(1) = 0
 alphav(1) = 1:               REM Lhomme's
 beltav(1) = 0
 alphac(1) = 1:               REM Lhomme's
 beltac(1) = 0
 alphaw(1) = 1:               REM Lhomme's
 beltaw(1) = 0
 REM belta(2) = 1
 beltaw(2) = 1
 beltav(2) = 1
 beltac(2) = 1

END IF


REM Stefan-Boltzman const. epsilon
epsilon = .0000000567#
REM emissivity of the ground and forest
emg = .97
emf = .97

av = 0
bv = 0
ac = 0
bc = 0

aw = 0
bw = 0
sigma = 0

IF (jday / 2 = INT(jday / 2) AND jh = 0) OR n2 < > n1 THEN
  n2 = n1
  x1 = jday / 365
  x2 = x1 * x1
  x3 = x1 * x2
  x4 = x3 * x1
  x5 = x4 * x1

  clai = 0:   REM initialize current LAI
  REM PRINT "lai", lai
  FOR i = 1 TO spec
     IF species$(i) = "pine" OR species$(i) = "palm" THEN
        clai(i) = 1 / 1.27 * (1.0989 - .4914 * x1 - .9142 * x2 + 9.3392 * x3 - 12.6096 * x4 +
4.6705 * x5)
          ELSEIF species$(i) = "cypress" THEN
            clai(i) = (.0793 - 6.5786 * x1 + 58.6035 * x2 - 139.2981 * x3 + 136.9783 * x4 - 49.8781
* x5)
          ELSEIF species$(i) = "nyssa" THEN
            clai(i) = (.0469 - 4.4462 * x1 + 36.4049 * x2 - 70.0226 * x3 + 52.8368 * x4 - 14.906 *
x5)
          END IF
          IF clai(i) < 0 THEN clai(i) = 0
          clai = clai(i) + clai
          ts(j) = 0: REM initialization
          REM PRINT "LAI", lai
          REM PRINT "jday, species, curr lai, clai(i)";
          REM PRINT jday, species$(i), clai, clai(i),
          REM PRINT "total", tottal
          REM INPUT "  ", a$
        NEXT
        REM PRINT "clai", clai
        REM INPUT "  ", a$



       REM This section should be improved in later versions
       REM calculating canopy storage capacity

       REM assume the average diameter of branches md = 3 cm
       REM assume mean DBH = 13 cm and area ratio of branch to stem is 1:1
       REM so the average diameter of branches and stems is 8 cm
       md = 8
       cm = 0

       FOR i = 1 TO spec
         cmp = 0
         cmc = 0
         cmo = 0
         REM PRINT "clai(i):", species$(i), clai(i)
         IF species$(i) = "pine" THEN
           cmp = (.278 + .074 * md) * bai * clai(i) / clai
         ELSEIF species$(i) = "cypress" THEN
           cmc = (.455 + .1 * md) * bai * clai(i) / clai
         ELSE
           cmo = (.044 + .088 * md) * bai * clai(i) / clai
         END IF
      NEXT
         cm = cm + clai * .04

          REM PRINT "lhomme-cm ", cm
          REM INPUT "  ", a
       FOR i = 1 TO n1
         sai(i) = 0
         lai(i) = 0
```

```
  lays(i) = 0
NEXT
   tst = 0!

REM calculate LAI of each species in each layer

FOR i = 1 TO n1
wei(i) = 0
lai(i) = 0
FOR j = 1 TO spec
   wei(i) = sslai(j, i) + wei(i):    REM total LAI in a layer
NEXT
lai(i) = wei(i) + lai(i - 1)
sai(i) = wei(i) + bai * vlai(i) + sai(i - 1)
REM PRINT "n, lai, sai", i, lai(i), sai(i)
REM INPUT "  ", a$
NEXT


FOR i = 1 TO n1:    REM calculating weighted leaf width of ith layer
  lays(i) = 0
  FOR j = 1 TO spec
    IF wei(i) > 0 THEN
    REM PRINT leafw(j)
    lays(i) = leafw(j) * sslai(j, i) * slai(j, i) / wei(i) + lays(i)
    END IF
  NEXT j
REM PRINT "leaf size in a layer:", lays(i)
REM INPUT " ", a$
NEXT i

oneday1 = jday
END IF

REM calculate solar angle
REM PRINT "day, hr", jday, jh
CALL sunangle(year, jday, jh, elev)


REM calculate aerodynamic conductance above the canopy
REM displacement height
disp = (.858 - .408 * EXP(-.328 * clai) / 3.14) * ht(0)
REM disp = 2 * ht(0) / 3
REM zero plane height
z0 = (.051 + .096 * (1 - EXP(-.611 * clai / 3.14))) * ht(0)
REM z0 = .13 * ht(0)
REM PRINT ht(0), disp, z0
REM friction velocity
REM ss = (ht(0) - disp) / z0
ss1 = (ht(0) + 2 - disp) / (ht(0) - disp)
REM PRINT "ss, ss1", ss, ss1
REM Monteith et. al, 1990 and Perssson and Lindroth (1994)
 gapm(0) = us * us / (wind + .01)

 gapm1(0) = 1 / (wind / (us * us) + 4 / us)
REM lhomme (1991)
REM  gah = .1681 * (wind + .01) / (LOG(ss) * LOG(ss1))
ga(0) = .1681 * (wind + .01) / (LOG(ss) * LOG(ss1))
REM ga(0) = gapm(0)
REM LOCATE 1, 10:
REM PRINT USING "  ####.##"; disp / ht(0); z0 / ht(0); gapm(0); gapm1(0); ga(0)
REM INPUT " ", a

REM Kaimal and Finnigan (1994) (same as above)
REM uu = .41 * (wind + .1) / LOG(ss)
REM ga(0) = .41 * uu / LOG(ss)
REM rb(0) = 1 / ga(0)
REM PRINT ga(0)

trr = 1 - 373.15 / (ta + 273.15)
ex = 13.3185 * trr - 1.976 * trr * trr - .6445 * trr * trr * trr - .1299 * trr * trr * trr * trr
es = 1013.25 * EXP(ex)
REM saturated vapor pressure (mbar)
ex1 = 13.3185 - 3.952 * trr - 1.9335 * trr * trr - .5196 * trr * trr * trr
        REM slope of vapor saturation curve
REM gamma = 6.6:   REM mb/k
gamma = .66:          REM psychrometric constant = cp*P/0.622L  mb/K
lamda = 593 - .57 * ta:        REM latent heat of vaporization cal/g
rho = 1140:                REM density of the air  (g/m3)
cp = .239:                 REM specific heat of air (cal/g/K)
IF rh! > 100! THEN rh = 100!
vpd = es - rh! * es / 100
REM  PRINT "hh--es -- rh -- vpd:", jh, es, rh, vpd



REM at the top of the canopy
wind0 = us * LOG(ht(0) - disp) / .41
wind0 = wind
REM PRINT "u/u*", wind, wind0
REM INPUT " ", a

con = 1 / 3: REM conversion factor from all-sided to projected.

FOR i = 1 TO n1
  IF sai(i) = sai(i - 1) THEN
    u(i) = wind0 * EXP(-.6 * (lai(i - 1) * con + .01))
    REM there is always some sai between any layers, 3 is LAI conv. factor
  ELSE
    u(i) = wind0 * EXP(-.6 * lai(i) * con): REM wind speed profile, Lhomme
  END IF
  REM PRINT "i, u", i, u(i)
  REM PRINT "i, sai(i)", i, sai(i)
  REM INPUT "  ", a$
  temp = ((lai(i) - lai(i - 1)) * con) / ((ht(i) - ht(i - 1)))
  REM temp = lai(i) * con / (ht(0) - ht(i))
  REM PRINT "dsai", temp
  REM INPUT "  ", a$
  IF temp = 0 THEN temp = .0001
  IF i = 1 THEN
    k(i) = (.4 / (temp * temp)) * (u(i) - wind0) / (ht(i) - ht(i - 1))
  ELSE
    k(i) = (.4 / (temp * temp)) * (u(i) - u(i - 1)) / (ht(i) - ht(i - 1))
  END IF


      REM diffisivity conductance

  REM IF i = 1 THEN
  REM ga1 = ga(1)
  REM ga(1) = ga(0)
  REM ELSE
  REM ga(i) = ga(i) / ga1 * ga(0)
  REM END IF

  REM ga(i) = ga(0) * EXP(-2.5 * (1 - (ht(i) + ht(i - 1)) / (2 * ht(0))))
  REM PRINT i, ga(0), ga(i)
  REM INPUT " ", a


  REM PRINT " ga(0); k(i)", ga(0), k(i)
  REM PRINT "du, dh", u(i) - u(i - 1), ht(i) - ht(i - 1)
      REM turbulent diffusivity profile
  IF lays(i) = 0 THEN lays(i) = .05
  rb(i) = 300 * (lays(i) / (u(i) + .001)) ^ .5

  REM rb(i) = 50 / (u(i) + .001) ^ .5
      REM boundary layer profile

  gb(i) = 1 / rb(i)
      REM boundary layer conductance

REM wet canopy boundary conductance
gw(i) = (lai(i) - lai(i - 1)) * gb(i)

  coef = SIN(elev * 3.1416 / 180)
  IF coef > .3 THEN
  rn(i) = so * EXP(-.5 * .35 * sai(i) / coef)
  par(i) = par * EXP(-.5 * .35 * sai(i) / coef)
  ELSE
  rn(i) = so * EXP(-.5 * .35 * sai(i) / .3)
  par(i) = par * EXP(-.5 * .35 * sai(i) / .3)
  END IF
```

```
        REM PRINT coef, so, rn(i), sai(i)

          gs(i) = 0


          FOR k = 1 TO spec
          REM IF i < n1 THEN

               f1 = par(i) / (par(i) + b0(k))
               REM PRINT "vpd, a0, exp", vpd, a0(k), EXP(-a0(k) * vpd)
               f2 = g0(k) + (gmax(k) - g0(k)) * EXP(-a0(k) * vpd)
               REM PRINT "f1, f2", f1, f2
             IF ta < t0(k) THEN
               f3 = 1 / (1 + s1(k) * (t0(k) - ta))
               REM PRINT "f3", f3
             ELSE
               f3 = 1 / (1 + s2(k) * (ta - t0(k)))
               REM PRINT "f3", f3
             END IF
               gss(k) = f1 * f2 * f3 / 40000:       REM to convert to m/s from mmol/m2/s
               REM IF i = 5 THEN
               REM PRINT "rn, vpd, species, gs:", rn(i), sslai(k, i), species$(k), gs(k) * 40000
               REM PRINT "g0, gmax", g0(k), gmax(k)
               REM PRINT "par, gs", par(i), gss(k) * 40000
               gss(k) = gss(k) * sslai(k, i) * con

               REM  PRINT "hh, species", jh, species$(k)
               REM  PRINT "par, vpd, ta", par, vpd, ta
               REM PRINT "par(i)", par(i)
               REM PRINT "f1,f2, f3", f1, f2, f3
               REM PRINT "i, k, gs(k): sslai(k,i)", i, k, gss(k) * 40000, sslai(k, i)
               REM INPUT " ", a$
               REM END IF
          REM ELSE
          REM      gs(n1) = 0
          REM END IF
          gs(i) = gs(i) + gss(k)
          gs = gs + gs(i)
          NEXT k
          REM PRINT "ga0, ga1", ga(0), ga(1)
          REM PRINT "i, u, gb, ga, gs, k"; USING "###.####"; i; u(i); gb(i); ga(i); k(i)

          REM PRINT "lai(i), gs, gb   "

          REM PRINT USING "####.######  "; lai(i); gs(i) * 40000; gb(i) * 40000; gb(i) * sai(i) / (gs(i)
+ .000001)
          REM INPUT "  ", a$

          IF sai(i) = sai(i - 1) THEN
          gec(i) = (.001) * gb(i) * con
          ELSE
```

```
 gec(i) = (lai(i) - lai(i - 1)) * con * gb(i)
 END IF

REM  PRINT gec(i) * 40000
REM   INPUT " ", a
REM gev(i) = dll * gb(i) * (gs(i)) / (gb(i) + gs(i))
       REM the horizontal conductance for vapor transfer in layer i
       REM 3 is a conversion factor from all-sided to projected gs
 REM PRINT "gb gs", gb(i), gs(i)
       REM the horizontal conductance for heat transfer in layer i

 d(i) = 1 / (gec(i) + delta / gamma * (gev(i) + .000001))
 REM PRINT "d(i)", d(i)


 IF ga(i) = 0 THEN ga(i) = .00000001#
 b(i) = -ga(i - 1) / ga(i)
 bw(i) = -ga(i - 1) / ga(i)
 cv(i) = -(gev(i)) / ga(i)

 REM c(i) = delta * (cc(i) - cv(i)) * d(i)
 REM a(i) = 1 - b(i) - cv(i) - c(i) * (gev(i)) / gamma
 av(i) = 1 - b(i) - cv(i)
 ac(i) = 1 - b(i) - cc(i)

 aw(i) = 1 - bw(i) - ccw(i)
 IF i = 2 THEN
 REM alpha(2) = a(1)
 alphav(2) = 1 - cv(1)
 alphac(2) = 1 - cc(1)

 alphaw(2) = a(1)
 END IF
 REM ef(i, i) = delta / (gec(i) + .000001)
 efv(i, i) = -1
 efc(i, i) = -1
 IF i > 1 THEN

 alphaw(i + 1) = aw(i) * alphaw(i) + bw(i) * alphaw(i - 1)
 beltaw(i + 1) = aw(i) * beltaw(i) + bw(i) * beltaw(i - 1)

 REM alpha(i + 1) = a(i) * alpha(i) + b(i) * alpha(i - 1)
 beltav(i + 1) = av(i) * beltav(i) + b(i) * beltav(i - 1)
 alphac(i + 1) = ac(i) * alphac(i) + b(i) * alphac(i - 1)
 beltac(i + 1) = ac(i) * beltac(i) + b(i) * beltac(i - 1)
 REM PRINT alphac(i + 1), beltac(i + 1)
 REM INPUT " ", a
 END IF
 REM PRINT "hh", jh
 REM PRINT "a(i), b(i), c(i)", a(i), b(i), c(i)
 REM PRINT "gev, gec, d, alpha, belta"
```

```
  REM PRINT gev(i), gec(i), d(i), alpha(i), belta(i)
  REM INPUT "  ", a$
REM ef(2, 1) = c(1)
efv(2, 1) = cv(1)
efc(2, 1) = cc(1)
IF i > 1 THEN
  FOR j = 1 TO i
   IF j < i - 1 THEN
     FOR j = 1 TO i - 2
     REM ef(i + 1, j) = a(i) * ef(i, j) + b(i) * ef(i - 1, j)
     efc(i + 1, j) = ac(i) * efc(i, j) + b(i) * efc(i - 1, j)
     NEXT
   END IF
   IF j = i THEN
     REM ef(i + 1, j) = c(i)
     efv(i + 1, j) = cv(i)
   END IF
   IF j = i - 1 THEN
     REM ef(i + 1, j) = a(i) * c(i - 1)
     efv(i + 1, j) = av(i) * cv(i - 1)
     efc(i + 1, j) = ac(i) * cc(i - 1)
   END IF
  NEXT j
END IF
  aw = aw + alphaw(i) * gw(i):      REM wet canopy
  bw = bw + beltaw(i) * gw(i):      REM wet canopy
  REM a! = a! + gec(i) * gev(i) * d(i) * alpha(i) / ga(0)
  REM a! = a! + gec(i) * gev(i) * d(i) * alpha(i) / ga(0)
  REM b! = b! + gec(i) * gev(i) * d(i) * belta(i) / ga(1)
  av = alphav(i) * gev(i) + av
  bv = beltav(i) * gev(i) + bv
  ac = alphac(i) * gec(i) + ac
  bc = beltac(i) * gec(i) + bc

NEXT i

REM PRINT ac, av, bc, bv
REM INPUT " ", a
REM PRINT ga(0), ga(1)
REM INPUT " ", a



FOR i = 1 TO nl
 ev(i) = 0
 ec(i) = 0
 FOR j = i TO nl
    REM e(i) = e(i)+ gec(j) * gev(j) * d(j) * ef(i, j)
   ev(i) = ev(i) - efv(j, i) * gev(j)
   ec(i) = ec(i) - efc(j, i) * gec(j)
   NEXT j
  NEXT i
tec = 0
etev = 0

FOR i = 1 TO n1
   gec(i) = gec(i) / con
   gs(i) = gs(i) / con
NEXT i

    REM PRINT tec, ta, etev, es
    REM INPUT " ", a
  REM PRINT "hh ", jh
  REM PRINT "a, b", a, b

  rcc = (1 + bc / ga(1)) / (ac + .0000001#)
  rcv = (1 + bv / ga(1)) / (av + .0000001)
  rcs = rcv - rcc
  REM rcs = rcv
  rca = 1 / ga(0) + rcc

  REM PRINT gapm(0), 1 / rca
  REM PRINT gs, 1 / rcs

  REM PRINT rcs, rca
  REM INPUT " ", b

 FOR i = 1 TO n1
    gec = gec + gec(i)
    gs = gs + gs(i)
 NEXT i


 REM lhomme's general equation
 rad = so
 energ = delta * (rad - rn(n1))
 vpd1 = rho * cp * vpd / (rca * con)
 REM vpd1 = rho * cp * gah * a * vpd
 REM PRINT " delta, rad, rn(n1)", delta, rad, rn(n1)
 bottom = lamda * (delta + gamma * (1 + rcs / rca))
 REM IF vpd1 > 0 THEN
 REM PRINT "ga(0)", ga(0), vpd
 REM PRINT "a, b", a, b
 REM PRINT "energy vdp1 sigma bot: "; USING " ####.##"; energ; vpd1; sigma; bottom
 REM INPUT "d:", d
 REM END IF

 IF d > .3 THEN
 tet = 3600 * (vpd1 + energ) / bottom / 1000: REM total et (mm; accounting for dryness)
 ELSE
 tet = 3600 * d / .3 * (vpd1 + energ) / bottom / 1000: REM total et (mm; accounting for dryness)
```

```
    REM g/m2 to mm
END IF
ttt = ttt + tet
REM PRINT USING "#.##   "; tet
REM IF jh = 23 THEN ttt = 0


REM Evaporation from water surface

REM zero plane displacement (roughness length) = 0.006 cm Eagleson, 1970

REM ss = ht(nl - 1) / (.2 / 100)
REM PRINT ht(nl - 1), u(nl - 1)
REM gat = .1681 * u(nl - 1) / (LOG(ss) * LOG(ss))
REM PRINT "gat   ", gat
REM  gat = ga(0) * EXP(-2 * (1 - .05 / ht(0)))
REM PRINT "ga(nl), ga(0)  ", ga(nl), ga(0)

REM convective energy from uplands top0

REM top0 = delta * .1 * so * (1 - EXP(-clai))
REM top0 = 0
REM assume 30% of Rn used for evaporation, the rest for temp increase
REM top1 = delta * rn(nl) * (1 - EXP(-(clai + .0001) / 3))
REM add = 1.5 - 3 * EXP(-clai / 2)
REM IF add < 0 THEN add = 0
REM top1 = delta * rn(nl) * add
REM top1 = 0
REM top2 = rho * cp * gat * vpd
REM botwet = (delta + gamma) * lamda
REM watet = 3600 * (top0 + top1 + top2) / botwet / 1000
REM PRINT top1, top2
REM INPUT " ", a
REM PRINT "                              dry -- watet: ";
REM wat = watet + wat
REM dayl = dayl + watet
REM PRINT USING "###.## "; wat; dayl; top0; top1; top2
REM IF jh = 23 THEN dayl = 0


 REM Multilayer Penman-Monteith equation
FOR i = 1 TO nl
 IF i = 1 THEN
    upp = rad
 ELSE
    upp = rn(i - 1)
 END IF
energ = delta * (upp - rn(i))
vpd1 = rho * cp * gec(i) * vpd
REM PRINT " delta, rad, rn(nl)", delta, rad, rn(nl)
REM IF gs(i) > .00001 THEN
REM PRINT USING "######.######  "; gs(i); gec(i); ga(i) / (gs(i) + .00000001#)
REM INPUT " ", a
REM END IF
REM PRINT gec(i) / (gs(i) + .000001)

IF gs(i) = 0 OR gev(i) = 0 THEN
   lay1 = 0
   lay2 = 0
ELSE
   bott = lamda * (delta + gamma * (1 + gec(i) / (gs(i) + .000000001#)))
REM PRINT lamda, delta, gamma
REM PRINT "energy vdp bot: "; USING " #######.###"; energ / bott; vpd1 / bott; bott
  REM PRINT "d:", d
IF d > .3 THEN
lay1 = 3600 * (vpd1 + energ) / bott / 1000: REM total et (mm; accounting for dryness)
lay2 = 3600 * (vpd / 1000) * gs(i) * 40 * 18 / 1000: REM total et (mm; accounting for dryness)
ELSE
lay1 = 3600 * d / .3 * (vpd1 + energ) / bott / 1000: REM total et (mm; accounting for dryness)
lay2 = 3600 * d / .3 * vpd * gs(i) * 40 * .018 / 1000: REM total et (mm; accounting for dryness)
      REM g/m2 to mm
END IF
END IF




IF sys$ < ss$ OR ss$ < sys$ THEN
   et11 = 0
   et21 = 0
   ss$ = sys$
END IF
hr1 = hr1 + lay1
hr2 = hr2 + lay2
et11 = et11 + lay1

et21 = lay2 + et21
day1 = day1 + lay1
day2 = day2 + lay2
REM PRINT et11, et21

REM wet canopy (interception)
REM bottom1 = lamda * (delta + gamma)
REM wetet1 = 3600 * (vpd1 + energ) / bottom1 / 1000: REM total et (mm; accounting for
dryness)
REM wetet = wetet + wetet1

IF jh = 23 THEN
   LOCATE 15, 40:
   PRINT USING " ####.## "; et11
REM    LOCATE 16, 40:
REM    PRINT USING "####.## "; et21
```

```
END IF


REM decoupling omega (Pinty et al., 1992, ...)
REM forest coverage
cov = 1 - EXP(-sai(i) / 3)
eps = epsilon * cov * emf * (1 + emg / (emf + emg - emf * emg))
REM radiative conductance
gr = 4 * eps * (ta + 273) ^ 3 / (rho * cp)
IF lai(i) = 0 OR gs(i) = 0 OR lai(i) = 0 THEN
omega10 = 0
ELSE
xx = 1 + bai(i) / lai(i) + gr / ((ga(i) * n1 + .00001))

REM 3 is the conversion factor from all-rounded to projected LAI
omega10 = (delta / gamma + xx) / (delta / gamma + xx * (1 + ga(i) / (gs(i) * n1 + .00001)))
END IF

omega1 = omega1 + omega10
REM gec = gec + gec(i)
REM gs = gs(i) + gs
REM IF jday = 150 THEN
REM PRINT "jday, jh, par", jday, jh, par
REM PRINT "Solar E.", coef
REM PRINT "f(par), f(vpd), f(ta)", f1, f2, f3
REM PRINT " gs", gs * 40000
REM INPUT " ", a
REM END IF


NEXT i

REM PRINT gr, gs, gec
REM INPUT " ", a
REM interception et
energ = delta * (so - rn(n1))
vpd1 = rho * cp * gapm(0) * vpd
bot1 = lamda * (delta + gamma)
wetet = 3600 * (vpd1 + energ) / bot1 / 1000
REM PRINT energ, vpd1, bot1
pet = 3.6 * (delta * so) / bot1
watet = .3 * pet




REM coupling to decoupling
omega1 = 1 - omega1

REM for the whole canopy  decoupling
REM IF gs > 0 THEN
```

```
    xx = 1 + bai / lai + gr / ((gapm(0) + .00001))
    omega2 = 1 - (delta / gamma + xx) / (delta / gamma + xx * (1 + gapm(0) / (gs + .00001)))

    LOCATE 1, 5:

    REM PRINT "  hr; omega; ga/gs; gec/gs; gr/ga"
    REM PRINT USING "  #####.##"; jh; omega2; gapm(0) / gs; gec / gs; gr / gapm(0); gs
    REM INPUT " ", a

    REM ELSE
    REM omega2 = 1
    REM END IF
    REM PRINT xx, gr / (gec + .00001)
    REM INPUT " ", a

    IF (jday / 30 = INT(jday / 30)) THEN
    PRINT #5, USING "######"; jday; jh;
    PRINT #5, USING "#####.##"; d; par; so; vpd; ta;
    PRINT #5, USING "#######.###   "; tet; hr1; hr2; watet;
    PRINT #5, USING "#######.###   "; gs * 40; ga(0) * 40; gec * 40; omega1; omega2; clai
    END IF

    hr1 = 0
    hr2 = 0

    IF jh = 12 THEN
    LOCATE 22, 40:
    PRINT USING "   ##.## "; omega2
REM        LOCATE 22, 55:
REM       PRINT "Min Omega: "; mino
    END IF


    REM calculating daily decoupling coef.
    omega1 = 1 - omega1
    omega2 = 1 - omega2
    tom1 = tom1 + omega1
    tom2 = tom2 + omega2
    tgec = tgec + gec
    tgs = tgs + gs
    tga = tga + ga(0)
    lhomm = ttt
    penman = day1

    flux = day2
    flux1 = flux
    REM PRINT "ET", tet, penman, flux
    jdd = -1
    IF jh = 0 AND ((jdd < jday) OR (jdd > jday)) THEN
    PRINT #6, USING "######"; jday;
    PRINT #6, USING " ######.###    "; lhomm; penman; flux; tgs * 40; tgec * 40; tga * 40; tom1;
```

```
tom2; clai
     tgs = 0
     tga = 0
     ttt = 0
     day1 = 0
     day2 = 0
     flux = 0
     tgec = 0
     tom1 = 0
     tom2 = 0
     jdd = jday
     END IF


     gec = 0
     gs = 0
     omega1 = 0
     omega2 = 0

END SUB


SUB pondevap (plot$, jday, wt, wate, ratio)


     REM calculating water surface area from water level
     IF (plot$ = "c" OR plot$ = "C") THEN
       maxh = .39
       a00 = 10824.87
       b = 29.61
       b0 = 68.84
       b1 = 728.22
       b2 = 68783.89
       b3 = 0
       b4 = 0
     END IF
     IF (plot$ = "k" OR plot$ = "K") THEN
       maxh = .74
       a00 = 25326.18
       b = 29.15
       b0 = 12925!
       b1 = -2298.31
       b2 = 25382.81
       b3 = -56005.74
       b4 = 76358.08
     END IF
     IF (plot$ = "n" OR plot$ = "N") THEN
       maxh = .35
       a00 = 8421.31
       b = 28.1
       b0 = -1202.68
```

```
    b1 = -10920.6
    b2 = 183640.62#
    b3 = -211073.6
    b4 = 0
  END IF

  h = wt - b
  h2 = h * h
  h3 = h2 * h
  h4 = h3 * h
  area = b0 + b1 * h + b2 * h2 + b3 * h3 + b4 * h4
  ratio = area / a00
  IF h < 0 THEN ratio = 0
  IF h > maxh THEN ratio = 1
  IF ratio < 0 THEN ratio = 0
  IF ratio > 1 THEN ratio = 1
  pondet = ratio * wate
  PRINT #30, USING " ### "; jday;
  PRINT #30, USING " ###.###"; h; ratio; wate; pondet
  REM LOCATE 23, 10:
  REM PRINT plot$, ratio, wt, h

END SUB


SUB soilevap (plot$, wt, ratio)

  decay = 4
  ratio = EXP(-decay * wt)
  IF ratio > 1 THEN ratio = 1

END SUB


SUB sunangle (year, day, hr, elev)
  zone = 5
  lat = 29.733
  dasvtm = 0
  lon = 82.158
  twopi = 6.2831853#
  rad = .017453293#
  lat = lat * rad

  h = (hr - 12) * 15 * rad
  d = 23.5 * COS((172 - day) * rad) * rad
  b = SIN(lat) * SIN(d) + COS(lat) * COS(d) * COS(h)
  elev = ATN(b / SQR(1 - b * b)) / rad
  REM LOCATE 12, 40
  REM IF hr = 12 THEN PRINT "elev", USING "##.#"; elev

END SUB
```

APPENDIX II
INPUT FILES TO ETM

1. Forest Structure

H_m, n, LAI, $N_{species}$

$H_n, H_{n-1}, H_{n-2}, \ldots, H_2, H_1$

$l_n, l_{n-1,} l_{n-2}, \ldots, l_2, l_1$

$species_1, DBH_1, H_1, D'_1, B/S_1, width_1, l_{species1}, p_{(n, 1)}, p_{(n-1, 1)}, \ldots, p_{(2, 1)}, p_{(1, 1)}$

......

$species_N, DBH_N, H_N, D'_N, B/S_N, width_N, l_{speciesN}, p_{(n,N)}, p_{(n-1, N)}, \ldots, p_{(2, N)}, p_{(1, N)}$

$g_{(m, 1)}, g_{(0, 1)}, b_{(0, 1)}, T_{(o, 1)}, c_{(0, 1)}, s_{(1, 1)}, s_{(2, 1)}$

......

$g_{(m, N)}, g_{(0, N)}, b_{(0, N)}, T_{(o, N)}, c_{(0, N)}, s_{(1, N)}, s_{(2, N)}$

Notes:

H_m	Maximum canopy height, in m
n	Number of layers
i	ith layer in the canopy. i = 1, 2, ..., n
LAI	Maximum LAI in a year, in m^2/m^2
$N_{species}$	Number of species in the forest
j	jth species in the forest. j=1, 2,..., $N_{species}$
H_i	The bottom height of the *i*th layer, in m.
l_i	LAI fraction in the *i*th layer.
$specie_j$	Name of species j.
DBH_j	Diameter at breast height of species j, in cm.
H_j	Average height of species j, in m.
D'_j	Stem density of species j, in stems ha^{-1}.
B/S_j	Ratio of branch surface area to stem surface area.
$width_j$	Width of a leaf/needle, in m.
$l_{speciesj}$	LAI weight of species j.
$p_{(i, j)}$	Presence (1) or absence of species j in layer i.
$g_{(m, j)}$	A coefficient in Jarvis' stomatal conductance model.
$g_{(0, j)}$	A coefficient in Jarvis' stomatal conductance model.
$b_{(0, j)}$	A coefficient in Jarvis' stomatal conductance model.
$T_{(o, j)}$	A coefficient in Jarvis' stomatal conductance model.
$c_{(0, j)}$	A coefficient in Jarvis' stomatal conductance model.
$s_{(1, j)}$	A coefficient in Jarvis' stomatal conductance model.
$s_{(2, j)}$	A coefficient in Jarvis' stomatal conductance model.

2. File Specifying the Time and Ecosystems of Interest

---

yr*1*, system*1*
yr*2*, system*2*
.
.
.
yr*n*, system*m*

Notes:

yr*i*	Year, expressed as XX. For example, 88 represent 1988.
system*j*	Name of the system. It is composed of system name ("p" for wetland and "u" for uplands) and site name. For example, np, ku, jackp.

3. Meteorological Input Data

Day	Hour	Rn	Ta	RH	PAR	Wind	Rain
4	0	0.000	16.130	78.400	0.000	8.060	0.000
4	1	0.000	16.790	77.800	0.000	7.680	0.000
4	2	0.000	16.780	78.100	0.000	6.340	0.000
4	3	0.001	17.580	78.300	0.000	7.900	0.000
4	4	0.001	18.290	78.500	0.000	9.590	0.000
4	5	0.000	18.630	79.000	0.000	8.710	0.000
4	6	0.000	18.720	80.000	0.000	7.270	0.000

4. Daily Water Table Data

yy	dd	wt
92	12	29.38
92	13	29.38
92	14	29.38
92	15	29.38
92	16	29.38
92	17	29.38
92	18	29.38
92	19	29.38
92	20	29.38
92	21	29.38
92	22	29.38

APPENDIX III
OUTPUT FILES FROM ETM

1. Daily Output Data

MM	day	rain	rad	ta	vpd	wind	PET	ET1	ET2	GCE	MPM	Wat	Se	W_e	int	D	tr_t	r_t	lai	Cm	WT
2	47	0.00	63.42	22.52	10.44	3.72	3.51	0.78	0.78	0.57	0.57	1.05	0.21	0.00	0.00	0.99	12	0	1.41	0.75	29.78
2	48	0.00	52.80	22.65	7.51	1.27	2.91	0.75	0.75	0.58	0.57	0.87	0.18	0.00	0.00	0.99	12	0	1.41	0.75	29.78
2	49	8.88	40.91	21.89	6.09	3.25	2.27	2.00	2.04	0.41	0.45	0.68	0.14	0.68	1.46	0.79	8	5	1.41	0.75	29.78
2	50	2.02	14.38	18.57	1.80	1.18	0.66	0.82	0.84	0.11	0.12	0.20	0.04	0.15	0.67	0.62	9	4	1.40	0.75	29.78
2	51	3.04	26.01	19.74	2.52	1.81	1.34	0.99	1.02	0.17	0.20	0.40	0.08	0.27	0.74	0.53	8	4	1.40	0.75	29.78
2	52	0.00	85.91	17.75	11.08	2.87	4.29	0.68	0.68	0.42	0.42	1.29	0.26	0.00	0.00	0.95	12	0	1.40	0.75	29.78
2	53	0.00	31.83	16.53	3.92	2.36	1.41	0.31	0.31	0.22	0.22	0.42	0.09	0.00	0.00	0.98	11	0	1.40	0.75	29.78
2	54	2.28	29.49	19.67	2.11	2.77	1.53	1.17	1.20	0.22	0.25	0.46	0.09	0.27	0.86	0.71	9	3	1.40	0.75	29.78
2	55	0.00	44.17	23.57	4.95	3.01	2.43	0.66	0.66	0.52	0.52	0.73	0.15	0.00	0.00	0.94	12	0	1.40	0.75	29.78
2	56	9.39	26.14	21.62	2.55	0.92	1.38	2.20	2.25	0.21	0.25	0.41	0.10	0.66	1.89	0.62	10	5	1.44	0.76	29.80
2	57	22.61	28.14	21.79	2.78	2.84	1.52	4.31	4.38	0.19	0.27	0.46	0.15	2.96	3.96	0.36	5	14	1.44	0.76	29.83
2	58	0.25	71.94	19.56	5.62	5.21	3.71	0.94	0.94	0.46	0.46	1.11	0.37	0.02	0.11	0.90	12	1	1.49	0.77	29.83
2	59	0.00	65.43	13.37	6.58	2.84	2.96	0.57	0.57	0.27	0.28	0.89	0.29	0.00	0.00	0.98	12	0	1.49	0.77	29.83

2. Hourly Output Data

jday	hour	D	PAR	RAD	VPD	Ta	GCE	MPM	Fick's	Water	gs	ga	gb	Ω	Omega	LAI
30	0	0.74	0.00	0.00	2.22	20.33	0.000	0.000	0.000	0.000	0.000	14.181	2.266	1.000	1.000	1.435
30	1	0.75	0.00	0.00	1.83	18.33	0.000	0.000	0.000	0.000	0.000	7.010	1.587	1.000	0.999	1.435
30	2	0.76	0.00	0.00	2.11	20.23	0.000	0.000	0.000	0.000	0.000	17.199	2.498	1.000	1.000	1.435
30	3	0.77	0.00	0.00	2.66	22.75	0.000	0.000	0.000	0.000	0.000	12.439	2.121	1.000	1.000	1.435
30	4	0.78	0.00	0.00	2.83	23.28	0.000	0.000	0.000	0.000	0.000	17.581	2.525	1.000	1.000	1.435
30	5	0.79	0.00	0.00	3.13	24.14	0.000	0.000	0.000	0.000	0.000	14.335	2.279	1.000	1.000	1.435
30	6	0.80	0.00	0.00	3.18	24.26	0.000	0.000	0.000	0.000	0.000	17.907	2.549	1.000	1.000	1.435
30	7	0.82	0.00	0.00	2.73	22.37	0.000	0.000	0.000	0.000	0.000	12.120	2.094	1.000	1.000	1.435

3. Monthly Output Data

```
                                  Monthly Sum of ET Simulation
                                              cp   91
                                       Canopy height  20  m
                               Number of layers used for simulation:  4
                                        Maximum LAI:  4.79
                                              BAI:  .8
                                  Number of species in the canopy:  3
                                  Height of each layer (m):  17  12  8  0
                                 Vertical distri. of LAI :  .25  .4  .25  .1
                               Species Name    Leaf Width    LAI weight
                                   cypress        0.002        0.500
                                   pine           0.005        0.360
                                   nyssa          0.050        0.140

mon Day  rain   rad.    Ta    VPD  wind   PET    ET1    ET2    GCE   MPM   Fick  Water  Sube  wete  int.  drye.  D    LAI   WT
 1  19  112.22 27.30  15.74  4.15  2.26  30.51  24.22  24.36  5.89  6.02  5.12   9.13  0.00 10.33 18.35  0.00  0.82  1.49  0.00
 2  28   23.33 48.92  17.82  7.89  2.78  67.04  17.29  17.40 11.46 11.57 10.17  20.12  0.00  3.04  5.83  0.00  0.93  1.42  0.00
 3  28  163.05 49.61  19.16  9.15  2.85  74.76  42.77  43.29 21.72 22.20 21.09  22.39  0.00 15.77 21.06  0.00  0.86  2.00  0.00
 4  30  137.62 61.69  24.97 11.29  2.37 112.26  76.76  77.02 51.54 51.81 51.00  33.69  0.00 17.38 25.20  0.00  0.90  3.03  0.00
 5  27   32.99 80.95  27.10 12.10  1.18 161.94 108.30 109.32 93.74 94.76 95.21  48.57  0.00  6.66 14.57  0.00  0.89  3.94  0.00
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BIOGRAPHICAL SKETCH

Shuguang Liu was born in Xiangtan county, Hunan province, the People's Republic of China (PRC), on December 2, 1963. He attended the First Middle School of Xiangtan from 1978 to 1980. He entered Central-South Forestry University, PRC, in 1980, and received his Bachelor of Science degree in 1984, with a major in forestry. He then entered Beijing Forestry University as a graduate student majoring in forest ecology and graduated with a Master of Science degree in 1987. He married his wife in Beijing, in 1991. He was employed by the Chinese Academy of Sciences and State Planning Commission from 1987 to 1992. During this period, he designed and implemented a Data Base Management System for China's Land Resources and participated in the Sino-Japan Collaborative Research Project on the ecology and hydrology of natural and deteriorated subtropical forest ecosystems in southern China. He came to the United States in 1992 to pursue a Ph.D. in forest hydrology at the University of Florida. He has held a graduate research assistantship in the School of Forest Resources and Conservation, and has participated in the research and modeling of the hydrology and ecology of the cypress wetlands and slash pine uplands in Florida flatwoods. He has been working on the scaling of the hydro-ecological processes in space and time. His first lovely daughter, Angela L. Liu, was born at the beginning of 1996.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Hans Riekerk

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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